Control of Fluidized Bed Tea Drying

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Cover design: From photographs of tea pluckers in the shadow of Mulanje Mountain.
Pen and ink drawing by Hazel Ashley

Propositions attached to the thesis

"Control of Fluidized Bed Tea Drying" by Stephen Temple.

1) To really understand a process, a mathematical model must be developed in parallel to an instinctive feeling for what is going on. If only one of the two components is present, wild deviations from reality are possible.
2) Limitations on a process such as drying, due to physical laws and properties, must be understood before research on biochemistry and quality aspects can proceed.
3) Tea drying is not just removal of water.
4) Tea dryer design is not a new art and has wider repercussions – where tea drying leads, other agricultural processes follow.
5) The more efficient a process engineer makes an operation, the more difficult the job of the control engineer becomes.
6) By setting the boundaries of a system to cover more of a process, the control system may be used to manage the disturbances rather than control the effects of the disturbances, thereby using fewer resources.
7) The constant rate phase of drying is a property of airflow rather than product.
8) Sophisticated control methods require sophisticated hardware and software for implementation; this makes off-the-shelf PID controllers attractive even where theory indicates that they are inadequate.
9) Control settings designed for stability are not necessarily optimal in terms of deviations.
10) Controller performance measures such as ISE, gain and phase margins which are important for one application may be found insignificant in others.
11) African agriculture cannot improve until farmers choose their profession, rather than it being the last resort.
12) Without email or rapid, cheap communications, collaborative research between continents is almost impossible.
13) "Timing Toast":

"There's an art of knowing when,

never try to guess,

toast until it smokes,

then twenty seconds less"

Piet Hein, More Grooks, Hodder Paperbacks, 1968

Dedication

This work is dedicated to the memory of the late Alan Johnson, a farsighted and stimulating engineer. After Alan first introduced me to the world of tea, he became a thought provoking colleague and a good friend. It is thanks to his foresight that there were experimental manufacturing facilities established at the Tea Research Foundation (Central Africa), without which none of this work would be possible. It is sad that he did not live to see some of the results from the programme he initiated.

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The author is indebted in particular to the support from Professor G. van Straten and Dr A.J.B. van Boxtel of the Systems and Control Group, Department of Agrotechnology and Food Sciences, Wageningen University. Their enthusiasm and encouragement provided the motivation to complete this study. Ton van Boxtel was able to visit Malawi, and welcomed me into his home in the Netherlands in addition to the academic support he provided.

None of this work would have been possible without the permission, support and encouragement from the Tea Research Foundation (Central Africa), its Director, Dr Adrian Whittle and the Chairman, Mr C. Barrow. Stimulation and criticism from colleagues in the tea industry in Southern Africa prevented the study from becoming too academic. The staff in the Manufacturing Research Facility and the laboratories at TRF were invaluable. In particular, my colleague, Sam Tambala, was able to take much of my routine workload to enable me to concentrate on these studies.

The work in Malawi was partly financed by European Union Stabex funds provided to the Tea Research Foundation (Central Africa) for a project on Automation of Tea Processing.

The biochemical part of the work was undertaken by the author's wife, Catherine. Her parallel studies, trials and tribulations put my own problems into perspective.

Contents

Summary

Tea is an important crop in several tropical and sub-tropical regions of the world. All of the various methods of processing tea require drying as a major part of the process, when the moisture content is reduced from about 70% to 3% wet basis. The duration of the drying process needs to be kept as short as possible to avoid losses in quality, but the temperatures to which the tea is exposed must be restricted to avoid damage to the quality. For a large proportion of the world's tea, and in particular in Southern Africa, drying takes place in a fluidized bed dryer.

The problem addressed by this study is the variation in moisture of the dry tea discharged from fluidized bed tea dryers. The objective is to develop a control system to achieve a reduction in this variation in discharge moisture content. As with many agricultural operations, the low value of the produce means that high cost instruments for process monitoring are not feasible commercially.

Currently dryers are manually controlled, and the standard of control of final moisture leaves much to be desired. There is a very sparse literature on tea manufacture, so before proceeding to a control system, the basic drying and fluidizing properties of tea were established by experiments to determine equilibrium moisture relations, thin layer drying characteristics and fluidization characteristics.

Equilibrium moisture values at drying temperatures were found to be very similar to published values determined for storage purposes of dried tea. Thin layer drying was found to be unexpectedly dependent on air flow velocity, but this could be explained by comparison of the particle characteristics with the properties of grain and other materials commonly investigated in such experiments. Fluidization of tea particles was found to be satisfactory only over a narrow range of superficial air velocities, ruling out air flow rate as a control variable. Further experiments established some limits for exposure of the drying material to elevated temperatures to avoid loss of quality but generating the blackness and associated reactions required.

To devise a control system for fluidized bed drying, a simulation model of the system was required. The first step in the simulation model development was a mathematical drying model for tea. This model was validated against some independent thin layer drying experiments, and the elements of the mathematical model were incorporated into a simulation model. The basic model simulates a batch fluidized bed dryer, with a fixed quantity of dry matter on the bed. This was validated against an experimental batch fluidized bed dryer. Good results were obtained but a calibration factor on the drying rate was found to be necessary to allow for the change from thin layer to fluidized bed.

The simulation model was extended to allow for the inflow of fresh material, building the material up to the level of the top of the discharge weir, then allowing excess material to be discharged over the weir. Because a commercial continuous flow fluidized bed dryer does not operate as a well-mixed system, but approximates to plug

flow, it was necessary to place several blocks representing well-mixed systems in series to simulate this condition. The continuous flow model was validated against a pilot-scale continuous dryer in the Manufacturing Research Facility, and a full-scale commercial dryer. The same calibration factor was found to apply as in the batch fluidized model.

Use of the simulation model revealed several operating characteristics of the dryers that had previously been suspected, but could not be quantified. The model formed the basis for design of a control system. The first stage was simple moisture feedback with a PI controller, which is difficult to implement in practice, as on-line moisture measurement is expensive and not very accurate. The use of a simple temperature feedback system could partially compensate for disturbances, but only to a limited extent. Large delays were found in the model, so dead time compensation using a Smith Predictor improved the controller. To improve on the limited performance of the temperature feedback system, an inferential estimator was designed. This provided similar performance to the moisture feedback system, but with simpler, lower cost measurement requirements. Some simplification of the standard inferential estimator could be achieved by using only gain ratios in the calculations, rather than full transfer functions. Comparing Bode plots of the full system with those of the simplified system validated this approach, allowing the controller to be implemented using off-the-shelf hardware.

The robustness of the control system under varying operating conditions was investigated. The controller tuning values obtained by standard methods such as Cohen and Coon or Ziegler-Nichols were found to become unstable under certain conditions. A different method of obtaining controller settings was devised, based on the simulation model. Gain margin, phase margin and integral squared error values were mapped onto axes of controller gain and integral time. This allowed selection of settings that could provide acceptable gain and phase margins while giving minimal integral squared error values. The values determined by this method were found to be stable over the whole range of operating conditions modelled.

A further use of the simulation model was to make a comparison of the types of dryer commonly used in the industry, and some other types. The fluidized bed dryer with recirculation was found the best compromise. The model was also used to design and build an end-point determination system to switch off a batch fluidized bed sample dryer when the sample was dry. The only manual input was the weight of material being loaded onto the dryer, and the pressing of a button to start the drying cycle.

The study required other work to be carried out, including the calibration of moisture measurement systems, the determination of some physical properties of tea and development of electronic systems for instrumentation and control. Furthermore several numerical approaches to improve the simulation model of the fluidized bed were explored in an attempt to eliminate the calibration factor.

This study was carried out to provide a means for reducing the variation in moisture content for tea discharged from a continuous fluidized bed dryer. Experimental work determined the drying characteristics of tea, and these formed the basis for a mathematical model of the drying process which was validated. A controller with the design based on simulation studies was shown to greatly reduce the moisture content variation. Both the model and the controller were shown to be insensitive to changes in the main variables. It is expected that the controller can be successfully introduced into industrial practice. This is the next step.

Samenvatting

Thee is een belangrijk gewas in verscheidene tropische en subtropische gebieden. Na het plukken van de theebladeren worden deze fabrieksmatig verwerkt tot het product dat de consument gebruikt. Een van de belangrijkste processtappen in de verwerking is het drogen waarbij het vochtgehalte van thee wordt teruggebracht van 70% naar 3%. De duur van het drogen moet zo kort mogelijk gehouden worden om kwaliteitsverlies te voorkomen, maar het gebruik van hoge temperaturen om de droogtijd kort te houden heeft ook nadelige gevolgen voor de kwaliteit. Door het gebruik van relatief milde temperaturen en een korte verblijftijd bieden gefluïdiseerd-bed drogers de mogelijkheid om aan de hoge kwaliteitseisen tegemoet te komen. Dit is de reden waarom een belangrijk deel van de theeproductie in de wereld, en vooral in zuidelijke deel van Afrika, met dit type droger wordt verwerkt.

Gefluïdiseerde-bed drogers worden nu handmatig bediend en geregeld, en de beheersing van het eindvochtgehalte laat veel te wensen over. Het ontwikkelen van een regeling voor zulke drogers is het onderwerp van dit proefschrift.

Uit literatuuronderzoek bleek dat er maar weinig kwantitatieve literatuur over de verwerking van thee beschikbaar is die direct gebruikt kon worden voor het ontwikkelen van een regelsysteem. Daarom is het onderzoek gestart met het experimenteel vaststellen van een aantal theeeigenschappen die van belang zijn bij het gefluïdiseerd-bed drogen. Deze gegevens zijn gebruikt als uitgangspunt voor vervolgexperimenten en om een droogmodel te bouwen.

Uit de experimentele resultaten blijkt dat waarden voor evenwichtvochtgehaltes van thee onder droogcondities overeen komen met eerder gepubliceerde waarden die gevonden zijn voor bewaarcondities van gedroogde thee. Uit dunne laag experimenten volgt dat de droogsnelheid van thee onverwacht gecorreleerd is met het debiet van de drooglucht. Door een vergelijking te maken met droogeigenschappen van graan en andere veel onderzochte agrarische producten is een verklaring voor dit resultaat gevonden. Fluïdisatie van theedeeltjes blijkt erg gevoelig voor het luchtdebiet en daarom kan maar een kleine variatie van het luchtdebiet worden toegepast. Dit maakt het luchtdebiet ongeschikt als variabele om het proces mee te regelen. En verder is het regelbereik van de luchttemperatuur, waarbij geen nadelige gevolgen voor de productkwaliteit optreden en voldoende zwartkleuring van thee bereikt wordt, vastgesteld.

Het ontwerp van een automatisch regelsysteem voor gefluïdiseerde bed drogers is gebaseerd op een simulatiemodel. De eerste stap in de modelontwikkeling was het opstellen van de mathematische vergelijkingen gebaseerd op massa- en enthalpiebalansen, en vervolgens de implementatie van deze vergelijkingen in een simulatieprogramma. In dit programma is de dunne laag (niet gefluïdiseerd) droogvergelijking gebruikt. Validatie van dit model voor een gefluïdiseerd bed droger die batchgewijs bedreven wordt toonde een systematisch verschil, maar na het

toepassen van een calibratiefactor op de droogvergelijking voor een dunne laag is een zeer goede overeenkomst tussen model en meting gevonden.

Het simulatiemodel is uitgebreid voor gefluïdiseerde bed drogers die continu bedreven worden. Dit model simuleert de gehele procesgang die begint bij een lege droger welke eerst gevuld wordt en, zodra de thee de ingestelde hoogte van de "overloop" bereikt heeft, als een continu proces bedreven wordt. Omdat commerciële gefluïdiseerde bed drogers niet de karakteristieken van een geroerde droger hebben maar veel meer die van een propstroom, is dit model samengesteld uit een serie van gemengde drogers. Dit model is gevalideerd voor metingen verricht aan de semi-industriële productie installatie van de Tea Research Foundation, en een commerciële theedroger van een theefabriek. In beide gevallen werd dezelfde waarde voor de calibratiefactor gevonden als voor de experimentele batch droger.

Het gebruik van het simulatiemodel leidde tot een kwantitatieve onderbouwing van verschillende niet gebruikelijke droogcondities en verder is het gebruikt voor het hoofddoel van dit onderzoek, namelijk het ontwikkelen van een regelsysteem. De eerste stap daarbij was de evaluatie van een standaard teruggekoppelde PI-regeling voor het vochtgehalte. Maar omdat on-line vochtgehalte meting duur en onnauwkeurig is, is deze regeling niet aantrekkelijk om te implementeren. Het alternatief, een directe terugkoppeling van de temperatuur van de lucht die de droger verlaat, is maar gedeeltelijk in staat om verstoringen in het proces te compenseren. Onder meer het voorkomen van significante "dode tijden" in de regelkring beperkt de kwaliteit van deze regeling. Dit probleem wordt ondervangen door het toepassen van een "Smith-predictor". De regeling is nog verder verbeterd door gebruik te maken van een "inferential schatter", dit is een algoritme dat op basis van onder andere de temperatuur van de uitgaande lucht verstoringen in het vochtgehalte schat. Hiermee wordt een vergelijkbare regelprestatie mogelijk als met de directe vochtgehalteregeling. De kosten van dit alternatief zijn belangrijk lager dan die van de directe vochtgehalte terugkoppeling en bovendien eenvoudig te implementeren.

In standaard "inferential schatters" worden volledige overdrachtfuncties toegepast, maar op basis van Bode-diagrammen bleek dat het gebruik van de stationaire gain ook voldoet. Deze eigenschap maakt de implementatie van de "inferential controller" eenvoudig en kan gerealiseerd worden met standaard apparatuur.

Een belangrijk criterium voor het gebruik van regelaars is robuustheid. Dit is de mate waarin zij voldoen onder variërende proces- en productcondities. De regelaarinstellingen die met de Ziegler en Nichols tuning regels gevonden zijn blijken onder bepaalde procescondities instabiel te worden. Daarom is een nieuwe tuning methode toegepast die ook gebruik maakt van het simulatiemodel. Combinatie van de gain- en fasemarge, en het geïntegreerde kwadraat van de regelafwijking uitgezet tegen de gain en integratietijd van de regelaar leverde een alternatief tuning resultaat. De resulterende waarden leveren een stabiel regelaargedrag voor de hele range van relevante proces- en productcondities.

Het simulatiemodel is ook gebruikt om een vergelijking te maken van verschillende in de theeindustrie toegepaste theedrogers. Hieruit bleek dat de gefluïdiseerd-bed droger de voorkeur verdient. Verder is het model als tool gebruikt bij het ontwerp van een automatische sturing van een batch-droger voor laboratorium toepassingen. Na het invoeren van het gewicht van het te drogen product, wordt het droogproces gestart en automatisch gestopt als het gewenste eindvochtgehalte bereikt is.

In dit onderzoek zijn diverse nevenaspecten aan de orde geweest. Dit betreft onder meer de calibratie van meetapparatuur voor het vochtgehalte in thee, de bepaling van fysische eigenschappen van het product, en de ontwikkeling van de elektronicacomponenten nodig voor de instrumentatie en het regelen. Tevens is nagegaan of door het toepassen van andere numerieke benaderingen de calibratiefactor geëlimineerd kan worden.

Dit onderzoek was gericht op het ontwikkelen van een methode om de variaties in het eindvochtgehalte van thee, die in gefluidiseerd bed installaties gedroogd wordt, te beperken. Bij de ontwikkeling daarvan is gebruik gemaakt van een wiskundig model. Diverse droogeigenschappen die nodig zijn voor dit model zijn via experimentele weg vastgelegd en bovendien is het model gevalideerd met onafhankelijke metingen. Door simulaties met het wiskundige model uit te voeren is een procesregeling ontworpen die de variaties in het vochtgehalte van thee aanzienlijk beperkt. Zowel het model als de procesregeling bleken ongevoelig voor de belangrijkste variaties die in het droogproces kunnen voorkomen. Daarom wordt verwacht dat de volgende stap, de introductie van de procesregeling in industriële omgevingen, met succes uitgevoerd kan worden.

1 Introduction

Although some herbal products are marketed as "tea", only teas manufactured from the shoots from the *Camellia sinensis* bush should really be sold as tea. *Camellia* was originally a plant of the jungle understory, in the region between Assam in India and China. It is now cultivated widely around the world, mainly in tropical and sub-tropical regions. In the Southern African region, the Tea Research Foundation (Central Africa), based in Malawi, is responsible for research activities. The tea growing areas in the region covered by TRF (CA) is shown in Fig. 1.1. The tea growing areas normally receive some rain almost every month, unlike many areas in the region which have a dry season from April to November. The first tea bushes in Malawi were planted in the early 1890s, and the crop has developed since then.

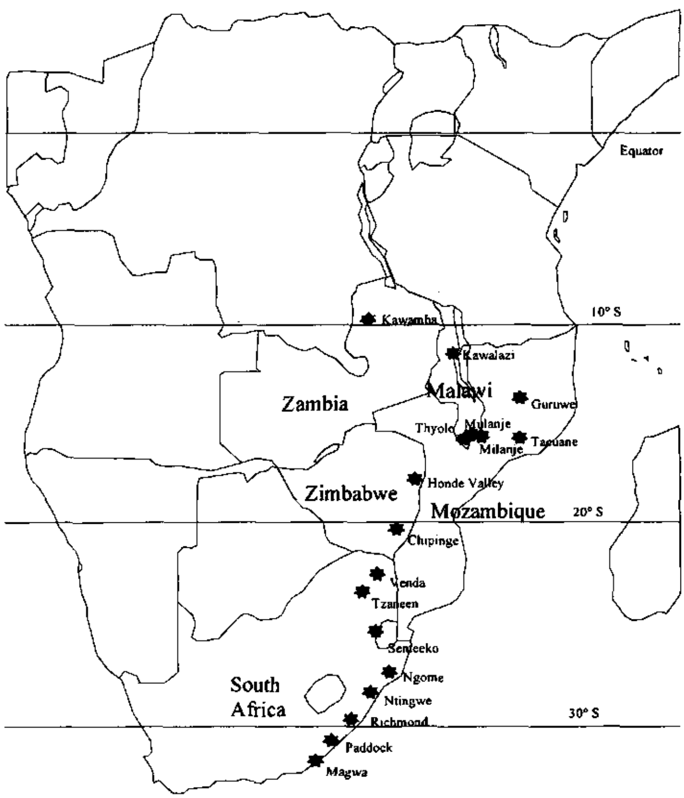

Fig. 1.1 Tea growing areas in Southern Africa

1.1 Tea growing

Bushes were originally grown from seed, but almost all recent plantings are vegetatively propagated from specially selected source bushes. Such teas are known as clonal, because all bushes are genetically identical. A recent development is the commercial utilisation of grafted plants, using for a rootstock plants selected for vigour and drought resistance and for the scion a high quality and high yielding clone.

The cuttings are propagated in a nursery under shade, and planted out into prepared holes in the field at about 18 months old. Without irrigation, the bushes take 5 or more years to reach their maximum yield; irrigation can speed up the rate of development dramatically. The bush can produce new shoots almost indefinitely if managed properly; there are bushes almost 100 years old in Malawi; however, as newer clones with higher quality and greater yield become available, it is prudent to replace the older varieties once they are 30 to 50 years old.

Harvesting the crop

The harvested part of the tea bush is the young, growing shoot comprising two or three leaves and the apical bud. Once a shoot has been harvested by plucking, a new bud on the stalk starts to develop. During the main growing season in Malawi, the time from bud initiation to reaching a pluckable shoot is 42 days. This period is influenced by temperature and light conditions, so will vary in different parts of the world and at different altitudes.

Pluckers will return to the same bush every 7, 10/11 or 14 days to pluck shoots that have grown to a pluckable stage. This means there will be 6, 4 or 3 different generations of shoot on the bush at any one time, respectively.

As plucking proceeds through the season, the height of the "plucking table" will increase with the growth of the stems. Every few years, pruning is carried out to bring this plucking table back down to a normal level, and to encourage the generation of new branches.

When the shoots are plucked, the moisture content is between 70% (in dry weather) up to over 80% in wet weather when the shoots are growing rapidly. In Malawi, yields of manufactured tea from one hectare can range from 1500 kg of dry, manufactured tea for seedling tea to 9000 kg for irrigated clonal tea.

In regions such as Kenya, where the tea is grown at high altitude with a well distributed annual rainfall, the crop yields hardly fluctuate from month to month. In Southern Africa the crop is grown at lower altitude where the rain is more seasonal and the temperature higher, there can be 90% of the annual yield produced in four months. Quality tends to be lower under low altitude, fast growing conditions.

1.2 Research into tea

World-wide there are several organisations looking at tea including well known institutes in Japan, China, India, Sri Lanka, Kenya and Malawi. The majority of the research effort goes into fieldwork: agronomy, physiology and plant breeding. Partly because of the high cost of equipping a research processing facility and associated biochemical instrumentation, very little systematic work has been carried out into tea manufacture. Instead much of the processing work is carried out in commercial tea factories or in miniaturised processing units where full control of the conditions is difficult to achieve. The more sophisticated studies into manufacture have concerned Orthodox and Green Teas, which concern whole leaf (see below). The literature on the processing of macerated teas as made in Southern Africa is sparse, and on some topics is non-existent. There is no quantitative work in the literature directly related to the drying of macerated black tea; the closest quantitative studies relate to equilibrium moisture determined for storage purposes.

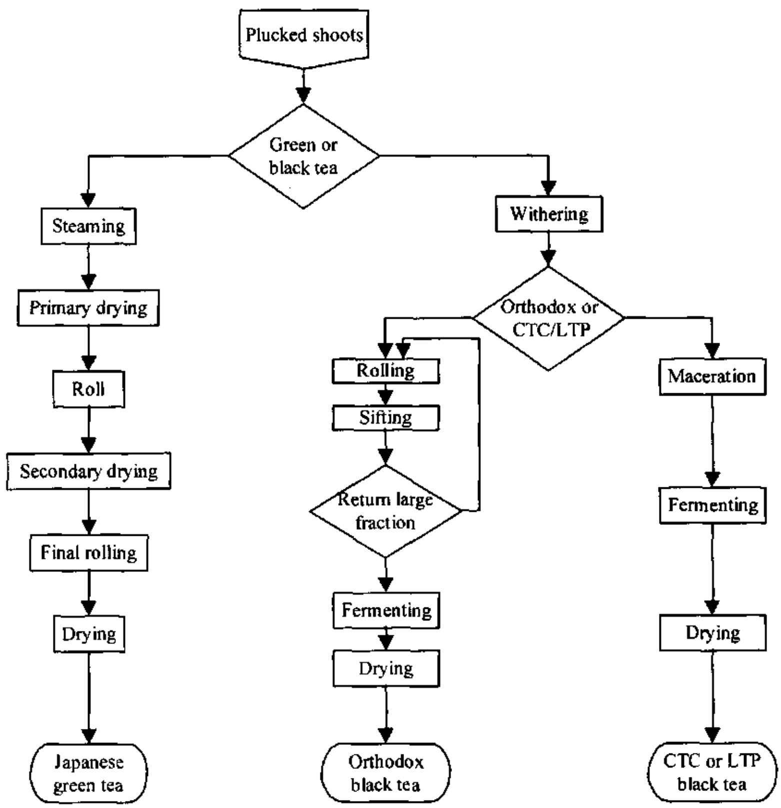

Fig. 1.2 Flow diagram for the manufacture of Japanese green tea, Orthodox and CTC black teas.

1.3 Tea manufacture – green and black teas

Tea can be processed in two main ways (Fig. 1.2). For green tea, enzymic action is killed off very early in the process using dry heat or steam but for black tea the enzymic oxidation is an important part of the process, termed by tea makers as "fermentation" although it is nothing of the sort

The majority of tea produced and drunk round the world is black tea; 2 028 thousand tonnes of black tea and 582 thousand tonnes of green tea were produced in 1996 (International Tea Council 1997). All of Japan's production, 71% of China's, 75% of Vietnam's and 20% of Indonesia's production is green tea, which makes up 98% of world green tea. A flow chart showing the main processes in three types of tea is shown in Fig. 1.2. From this point on, all discussion will refer to black tea only, and Fig. 1.3 illustrates the sequence of machinery used in the manufacture of black tea.

1.3.1 Withering

After plucking, tea shoots are collected and taken to a factory for processing; it is important that minimal damage occurs to the shoots at this stage from heat or mechanical handling, as this can affect the quality of the final product.

On arrival at the tea factory, the shoots are spread out in layers generally no more than 300 mm thick, so that air can be blown through the leaf mass to stop the temperature rising from respiratory heating, and to reduce the moisture content. This process is termed withering. The target moisture content at the end of the withering phase will depend on the method of cell disruption to be employed, but will range from 72% down to 55% moisture content. During withering, which can take between 4 and 20 hours in normal circumstances, biochemical changes occur which can be advantageous to quality, although research findings are contradictory. When atmospheric conditions are suitable, ambient air is used for withering, moved through the shoots by axial fans. If the ambient humidity is so high that the rate of moisture loss is inadequate, the air is heated before being blown through the leaf; this is avoided whenever possible as the effects are deleterious to quality. The duration of withering will depend as much on the factory loading as anything else; it is often forgotten that withering is mainly a stockholding operation buffering the leaf supply from plucking which occurs in daylight only, to manufacturing which takes place for 23 hours per day in peak season. Some systems separate the stockholding and chemical change phase from the moisture removal phase. The "chemical wither" takes place in deep tanks, up to 2 metres in depth, with just enough ventilation to avoid self-heating of the shoots.

Withering is essentially a batch process, although attempts have been made to employ continuous withering machines. The batch nature of the process allows for different moisture contents of leaf arriving at random times during the day; it also allows for manufacture of similar types of leaf in sequence, even though their arrival at the factory is interspersed with other types of leaf.

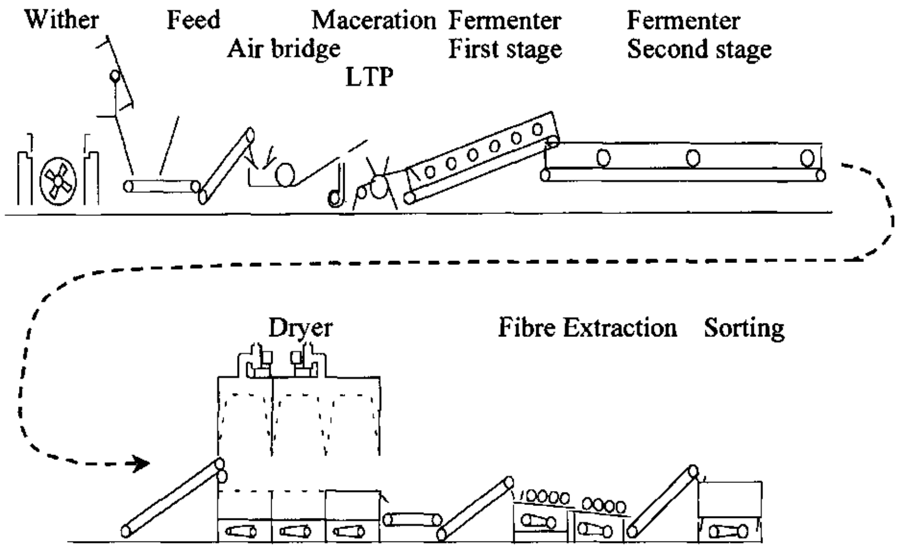

Fig. 1.3 Schematic diagram of LTP black tea manufacturing process.

1.3.2 Rolling or maceration

After withering, the shoots are rolled or macerated to break up the cell structure, releasing the enzyme systems to start the "fermenting" process. Rolling is used in the "Orthodox" method of tea manufacture, and results in whole leaf tea. To disrupt the cell membranes, a wither down to about 55% moisture is required before the rolling process. The alternative system involves cutting the leaf into particles of 1 mm or less in size, while totally disrupting the cell structure mechanically during the cutting process. The original method for this process was the Cut, Tear and Curl (CTC) machine, but in Southern Africa the Lawrie Tea Processor (LTP, derived from a hammer mill) is commonly used. In 1996, Asia produced 760 000 tonnes of CTC tea against 670 000 of Orthodox while Africa produced 375 000 tonnes of CTC and LTP but only 8 000 of Orthodox tea.

1.3.3 Fermentation

After rolling or maceration has broken down the cellular structure of the leaf, the enzymic fermentation process starts. Air is introduced into the bulk of the dhool (as the macerated leaf is known) for cooling and to provide the oxygen required for the various reactions taking place. Some of the more important reactions taking place at this time are the oxidation of catechins followed by condensation to form theaflavins and thearubigens. The dhool colour will change from green to brown as the reactions take place.

Depending on the enzyme activity level in the leaf, and the dhool temperature, the fermenting stage can take from 45 minutes to over two hours to reach the optimum quality level. If fermenting is too short, there may be unused catechins, or inadequate levels of thearubigens; if too long, then the desirable theaflavins are converted into thearubigens. Drying arrests fermenting; if the early stages of drying are slow then accelerated fermenting reactions deleterious to quality may take place.

1.3.4 Drying – energy sources

Tea is universally dried by convective drying employing hot air; some experiments have been carried out with radio-frequency heating, vacuum drying and other techniques but hot air is the only practicable method on a commercial scale. The source of hot air may be from a flue gas to air heat exchanger ("stove"), from steam to air heat exchangers where the steam comes from a boiler fired on fuel-wood or coal, or from direct application of the products of combustion from oil, gas or gasified fuel-wood.

The boiler and steam system is the most capital intensive and least fuel efficient, but it is easier to maintain a stable temperature. Control of temperatures in a boiler system is most often by manual observation of the boiler pressure gauge; occasionally a thermostatic modulating valve may be fitted to one of the radiators in a bank. As there is heat exchange between the flue gases and steam, then between the steam and air, there are more opportunities for inefficiency.

Stoves are mostly used with the older type of dryers requiring an inlet temperature around 100°C; the old cast iron types are now difficult to maintain and there is room in the market for the design of a new heat exchanger. These are intermediate in fuel efficiency between boilers and direct firing. Because there is less thermal mass than in a boiler system, temperatures are less stable; control is manual, by observation of a hot air thermometer.

Both stoves and boilers are commonly fuelled by firewood, most often of *Eucalyptus spp.* grown on marginal areas of the tea estate. Very high yields of wood (up to 120 m^3/ha per year mean annual increment) can be obtained in tea growing areas with high rainfall.

Direct firing (without any form of heat exchanger) using oil or gas is uncommon in Africa as these fuels are not locally produced and are therefore expensive relative to fuel wood. To use the exhaust gases from burning wood is liable to taint the tea unless very high temperature, efficient combustion is used. To ensure this occurs, the wood may be pyrolysed ("gasified") and the gases are then burnt to produce an exhaust gas at a very high temperature. To be usable for drying, cold air must be blended with this exhaust to give suitable inlet temperatures. The thermal mass in such a system is minimal, and without an automatic control system the temperature would be impossible to control. PID controllers are used to operate the combustion air dampers and the ambient to flue gas blending valves to obtain a stable temperature. As there are no flue losses with this system, the energy efficiency is highest.

To demonstrate the quantities of water to be removed and wood to be burnt, the schematic diagram Fig. 1.4 illustrates that for every ton of tea leaving the factory, approximately 9 tons of material enter the factory. The balance of 8 tons comprises water vapour and flue gas, all of which is carried away in the atmosphere. The electrical requirement is not shown here, but can form almost half the running costs of a tea factory.

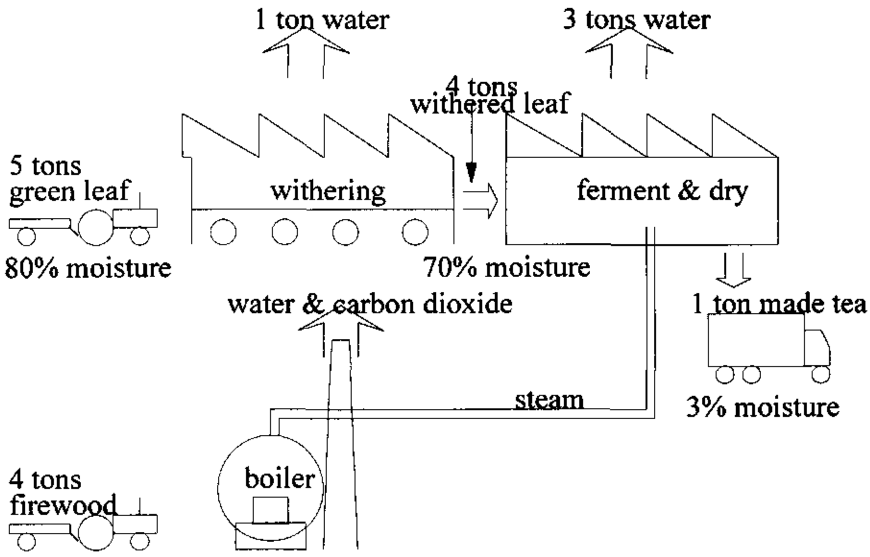

Fig. 1.4. Schematic diagram of mass flows in a tea factory

1.3.5 Drying – changes in the tea particles

The dhool is fed into the dryer at around 71% moisture content wet basis, with a target final moisture of 3%. This means that every 100 kg of dhool fed in will produce about 30 kg of made tea. Chlorophyll breakdown and Maillard reactions due to the temperature in the dryer will result in the brown colour changing to black, which is desirable, but if allowed to proceed at too high a temperature will result in a "bakey" or "high fired" off flavour, detracting from quality. If there is excessive mechanical action rubbing the tea particles against one another or against the machinery, the leaf hairs which may contain some of the flavour chemicals will be knocked off the tea particles and lost with the exhaust air; this is known as loss of bloom.

1.3.6 Drying – types of dryer

There are two types of dryer in use in the tea industry; the first has been used since 1907 and is known as the ECP (Endless Chain Plate or Endless Chain Pressure) dryer. The second is the fluid bed dryer that was first developed for tea in Sri Lanka in 1974 (Kirtisinghe 1974).

The ECP dryer (Fig. 1.5) consists of four or more conveyors made up of perforated metal trays attached to roller chains on either side. The dhool is fed into the top tray, and emerges from the bottom tray.

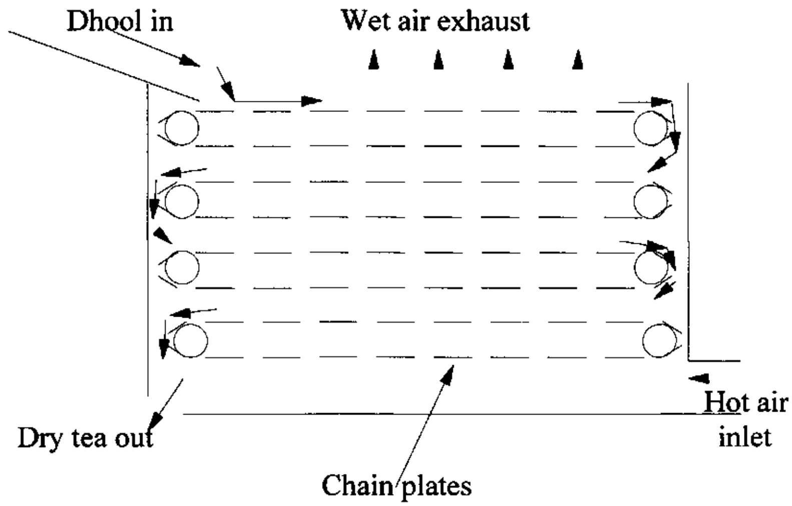

Fig. 1.5. Schematic diagram of ECP dryer.

Effectively, this type of dryer is a combination of cross flow and countercurrent, with the driest tea meeting the hottest air. The exhaust air will be close to saturation, so the air is used very efficiently. There are three main drawbacks with this type of dryer; the inlet temperature is limited to the maximum that the dry tea can be exposed to without loss of quality. The air meeting the new dhool is almost saturated, so the drying rate at this point is low but the temperature is higher than used for fermenting; this can lead to unwanted reactions and loss of quality. Finally, the hot drying chamber contains moving parts that are in contact with the tea, cannot be lubricated and are difficult to maintain.

The fluid bed dryer is mechanically much simpler, in its basic form (Fig. 1.6) consisting of a perforated bed plate, through which hot air rises, surrounded by side plates which contain the drying material. The dhool is fed at one end; at the opposite end the side plate is lower than all the others and acts as a weir. When the tea level is higher than the weir it will flow out over the weir.

Because the air flow rate through the bed fluidizes the particles in the bed, the material will find its own level and material fed in at one end will cause material to be discharged at the opposite end. It is essentially a cross flow type of dryer, with the same hot air meeting all the material in the dryer.

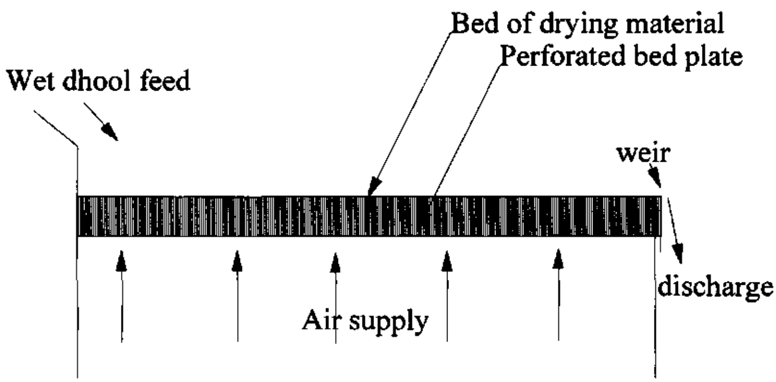

Fig. 1.6. Basic fluid bed dryer

At the wet end, drying will be rapid and the air use efficient, leading to a saturated exhaust. Evaporative cooling keeps the tea particles at a low temperature, avoiding quality loss. At the dry end, because the drying rate is limited, the air will pick up little moisture and will not be used very efficiently. Improvements on the basic dryer include having two or more separate air supplies, generally with hotter air at the feed end where drying can be more rapid and cooler air at the dry end where loss of quality can occur. To improve the efficiency of air use, the exhaust air from the dry end, which is far from saturation, can be recycled through the heater units once any light particles have been removed.

The fluid bed dryer looks a very simple machine, but because the material being dried is changing in density and moisture content as it passes through the dryer, its speed and drying rate will be very difficult to estimate. It is suspected that the time taken from making a change in conditions to reaching a stable operating point is at least 20 minutes, making manual control difficult.

1.3.7 Sorting

After drying, the fibrous particles from the stalk and leaf midrib are separated from the black tea particles by electrostatically charged rollers. This process works best when the relative humidity is very low and the tea is hot and dry, so is carried out immediately after drying. Vibrating or oscillating screens are used to sort the black tea particles into various size grades.

1.3.8 Storage and packing

To consolidate a batch of a single grade of tea for sale, the sorted teas are stored in bins where the moisture absorption will be less than if exposed to the atmosphere. Once enough tea has accumulated to pack a batch, it is loaded into multi-wall aluminium foil lined paper sacks ready for sale and dispatch.

1.3.9 Qualities of teas

Flavour or character of tea arises from volatile aldehydes, which are mainly formed from fatty acids and chlorophyll breakdown products throughout the process. Some of these compounds are desirable, others detract from the value. They are more prominent in high grown teas, and are not important in Southern African teas at present.

The actual colour of the tea liquor without and after adding milk is assessed as a quality parameter. Different colours are required for blending. Brightness is an aspect of colour which is assessed separately, the opposite of which is termed dull. A dull liquor can arise from excessive fermenting or a slow start to drying. Thearubigens contribute a large part of the colour of tea liquors.

Briskness is a mouth-feel characteristic of tea, mainly dependent on theaflavin content.

Although the purchaser of teabags does not see the colour of the black tea, tea buyers require a black rather than a brown colour. Contributions from chlorophyll breakdown products, gallic acid and Maillard reaction products form the black colour.

Particle size and packing density are important parameters in terms of how well tea bag packing machinery can handle the product. If it cannot be filled into teabags rapidly and takes up too much space in the bag, it cannot be used for this purpose and looses value accordingly. Particle size is determined partly by the cutting process, and together with density, by the amount of shrinkage in subsequent processes. Withering can affect density by shrinkage before cutting.

Bloom is assessed by inspection of the dry black tea. If the leaf hairs, or the dried products of fermentation, have been knocked off the tea particles by excessive mechanical handling when dry, the tea will look grey rather than black.

1.4 The need for control systems in tea processing.

To compete on the world market, a tea producer needs to be able to offer for sale tea of a consistent quality, at a moisture content low enough to prevent loss of quality during storage and distribution. An increasing demand is for a particle size and packing density suitable for use with high-speed tea bag making machinery. Although it has not yet been taken up by the industry, it is likely that buyers will insist on quality management systems such as the ISO 9000 series. During the production process costs must be kept down; in common with many primary producers, the power of the multi-national buyers squeezes the profit margins of the producer to an absolute minimum. Control systems may be able to maintain product quality while reducing production costs.

1.4.1 Withering

The main objective of withering is to remove moisture from the shoots to a defined target level, while maintaining quality. Control is achieved by controlling the airflow through the bulk of tea shoots, normally as an on/off control. The minimal amount of energy should be used, and as this is mostly electrical energy, the cost implications are important. Withering is mainly carried out as a batch operation with the endpoint determined by manual observation.

Developing a control system for withering which could manage fan operation for all withering troughs in a factory, minimising the electrical energy and maximum demand for electrical energy would be very useful, but would depend on a predictive method as the sensing for feedback operation is not simple to implement. A project at Tea Research Foundation (Central Africa) is looking at some of the possibilities for predictive control.

1.4.2 Fermenting

The variables to be controlled in fermenting are the airflow through the dhool and the time on the fermenter. The airflow settings are limited to a maximum where dhool is blown out of the fermenter, and would be difficult to determine automatically. Fermenting time is determined by finding a peak of quality, which could possibly be achieved by some type of on line sensing. No such system has yet been devised, although current work at the Tea Research Foundation (Central Africa) is investigating some of the options.

1.4.3 Drying

The objective of drying is primarily achieving a target moisture content, with minimal use of energy and the minimal loss in quality. As the discharge from the dryer is a continuous stream, finely macerated and relatively homogenous, on-line moisture measurement should be possible using near-infrared techniques. If such a method is not feasible for commercial use, the temperature profile within the dryer might be used to infer the moisture content value.

Airflows can be varied quite simply by the use of dampers in the supply duct; more energy efficient methods such as variable speed drives or inlet guide vanes are more complex but could be used once the control system has been validated.

Thermostatic or electrically controlled valves on the radiator banks can control temperatures on a boiler/steam radiator system.

The fluidization and drying characteristics of tea have not been published in the literature, at least for black CTC type teas. The fluid bed dryer is a popular method of drying, but is little understood by its users. The method of operation is determined by trial and error in practice. As the system takes some time to stabilise after an adjustment has been made this is not easy. To illustrate this, Kandappah and

Samarasingham (1991) published the results of a survey of dryer discharge moistures in Sri Lanka, which are shown in Table 1.1.

Table 1.1. The range of moisture content (%) of dryer mouth teas

Factory	Mean	S.D.	No of observations
1	3.23	1.07	4
2	5.93	3.16	7
3	2.48	0.67	8
4	6.70	1.70	7
5	3.06	1.29	8
6	9.77	8.38	13
7	5.37	1.21	7
8	2.50	0.65	7
9	10.33	3.38	9
10	2.82	0.34	5
11	12.20	7.04	7
12	2.33	0.85	10
13	3.93	1.33	10
14	3.41	1.81	10
15	7.65	1.99	10
16	6.30	1.52	10
17	3.26	0.30	5
18	7.80	2.64	10
19	5.62	3.43	5
20	4.54	1.00	10
21	4.18	1.57	5
22	5.86	1.42	12
23	6.98	1.89	5

It is clear from this table that of the 23 factories, only factory 10 and factory 17 were controlling moisture anywhere near the specification of 3% ± 0.5%. Factories 1, 3, 8 and 14 had an acceptable mean value but a high standard deviation while the remaining 17 factories were failing to dry their teas anywhere near the target moisture. The worst two had a mean of 9.77 with standard deviation of 8.38 and a mean of 12.2 and a standard deviation of 7.04. Clearly this problem must be addressed.

The only reports covering control of tea drying describe work with green tea. Yin Hongfan *et al* (1988) derive a relationship between leaf temperature and moisture content, then use this to implement predictive control. Their conclusion is that there is a substantial economic benefit. Yoshitomi and Sumikawa (1995) describe a system of supervisory control for each of the six sub-processes in Japanese green tea manufacture. At each stage several parameters are measured, and flow rates, temperatures and machine speeds controlled.

1.5 Problem definition and objectives

Control of fluid bed drying should be investigated. If a suitable method of control can be determined, it should be relatively simple to implement by attachment of electrical actuators to the existing manual controls. This study aims to investigate the feasibility of automatic control of the fluid bed dryer. Initially a three-stage dryer with a single outlet weir should be considered; once this system has been investigated, other configurations will involve minor modifications.

An approach to the topic through modelling can give generally applicable results, and if the model is configured in a suitable fashion, modules can be arranged in various ways to suit different configurations of dryer found in commercial tea factories.

To develop a model there needs to be a better understanding of the processes involved in drying tea. The driving force for drying is often taken to depend on the difference between the actual and the equilibrium moisture content relative to the drying air conditions. There is no literature on how the rate of drying of macerated tea depends on temperature and airflow, as well as other factors such as type of cut and variety (or clone) of tea. Work is required to understand the effects of the variables in tea drying on the drying rate.

In a fluidized bed dryer, the fluidization of the bed will depend on the characteristics of the material and the airflow. Again there is no literature relating to the airflow requirements for fluidization of tea, so work must be carried out on this topic also.

Once these factors have been quantified, a mathematical model and a simulation model of fluid bed drying can be developed and tested against practical dryers. The simulation model can then be utilised in the design of a control system.

The objectives of this study are:

- Investigate the equilibrium moisture relations of tea.
- Investigate factors affecting the drying rate of tea.
- Investigate the airflow requirements for fluidization of tea
- Investigate how tea quality is affected by drying conditions, to avoid adverse effects
- Develop a mathematical and a simulation model of fluid bed tea drying.
- Investigate the feasibility of a control system for fluid bed dryers.
- Compare different types of dryer in terms of efficiency and controllability

An outline of the work is shown in Fig. 1.7. Other ancillary work will also be included, for example to determine an effective means of measuring moisture content of tea in an on-line or at-line situation.

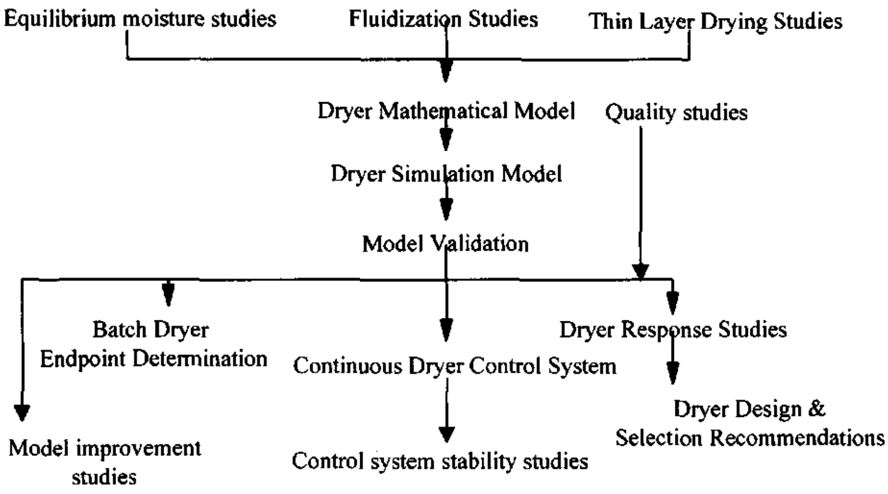

Fig. 1.7. Scheme of work

1.6 References

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2 Equilibrium Moisture Content of Tea*

2.1 Abstract

A method of measuring equilibrium moisture content relations for tea was investigated at temperatures from ambient up to 90°C used in drying. The method used a high temperature chilled mirror dewpoint meter with the sample in a sealed chamber in a temperature-controlled oven. Computer control is essential for the system and made it possible to detect stable conditions and to move to the next set of measurements. As a consequence the time needed for collecting data for sorption isotherms was significantly reduced in comparison to the saturated salt solution method. In this study the equilibrium moisture content of Central African tea under drying conditions has been measured. No consistent rate of change with temperature could be determined. Several isotherm equations were fitted to the data, and the Guggenheim Anderson de Boer model was found to give the best fit. Validation measurements of the equilibrium moisture content of tea to compare the dewpoint meter method with the usual saturated salt method on ungraded black teas gave comparable results.

2.2 Introduction

Equilibrium moisture content is defined as the moisture content of a hygroscopic material in equilibrium with a particular environment (temperature and relative humidity). Values from equilibrium moisture studies are important for knowing how a material absorbs and loses moisture during storage and for defining the storage conditions in order to obtain the best quality product. Moreover, simulation models for dryer design, dryer optimisation and control for several agricultural products use the difference between the actual moisture content and the equilibrium moisture as a measure for the driving force for drying.

During the manufacture of black tea, the macerated leaf (termed "dhool") which has undergone "fermentation" in tea terminology (actually enzymic oxidation) is then dried from around 70% w.b. moisture content to a target moisture content of 3% w.b. Some sorption of moisture during sorting and packing takes place so the packed product remains below 7% w.b. As the moisture content is reduced to such a low level compared to most agricultural products, equilibrium moisture content (EMC) plays a particularly important role at the end of drying.

Previous studies have looked at near-ambient conditions for storage of tea. Jayaratnam and Kirtisinghe (1974a, 1974b) used saturated salt solutions to determine

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the EMC values for a sorted black tea at 20°C. Thevathasan and Samaraweera (1985) used an electronic meter sensing air humidity to measure water activity of samples taken during drying, at temperatures between 20 and 24°C. Water activity is an alternative method of describing equilibrium relative humidity, and is expressed as a percentage. Their work was extended (Thevathasan & Samaraweera, 1989) by separating the drying particles into different size grades and measuring the water activity of individual size groups separately. No significant difference was found over a particle size range of 0.5 mm to 1.68 mm. Studies on black teas from Kenya using the saturated salt method were carried out by Dougan *et al.* (1979). Hampton (1992) gives other values but the grade and type of tea is not given.

The data from these studies needs to be fitted to a mathematical model for ease of use in drying work. Parry (1985) reviewed various approaches to modelling equilibrium moistures for grain and concluded that theoretical and semi-empirical models were not generally applicable over the entire range of relative humidity, recommending that empirical fits be used for greater accuracy. Lomauro *et al.* (1985) attempted to fit data from tea to various equations, concluding that the Guggenheim–Anderson–de Boer (GAB) model (Bizot *et al.* 1983) showed the best fit, followed by the Oswin (1946) model.

Drying of tea generally takes place under elevated temperature conditions. The product temperature ranges from 30 up to 90°C under extreme conditions. Therefore, to explore and predict the behaviour during drying of tea its equilibrium moisture content must be determined for a range of temperatures and relative humidities. Although in the literature equilibrium moisture data on tea is presented, it is not clear whether these results are valid for tea of other origin, for tea samples under drying conditions and for tea manufactured by the method used in the Central African tea factories, or whether sorted and unsorted samples behave in the same way. Determination of the equilibrium moisture of Central Africa ex-dryer (unsorted) tea and comparison with available data is therefore of significant importance.

For some environmental conditions, the product submitted to the saturated salt method used by many workers in this field takes many days to reach equilibrium, even for finely divided products such as black tea. This restricts the use of the method to low moisture content samples, otherwise fungal growth changes the characteristics of the material. Another limiting factor with this method is that many of the salts are only characterised over a narrow band of temperature near ambient. Finally, because of its long equilibration time, the saturated salt solution method is not very attractive. Therefore, a fast computer controlled measurement method was designed and evaluated. The objective is to produce data on equilibrium moisture of tea in a form that can be used in modelling the drying process, and should therefore be simple to calculate.

2.3 *Materials & Methods*

The tea used for these studies was *Camellia sinensis var. assamica*, grown and processed at the Tea Research Foundation (Central Africa) by the Lawrie Tea Processor (LTP), continuous fermenter and fluidized bed dryer method commonly used in the Southern African region.

The saturated salt method controls the humidity of the air in equilibrium with the test material for a certain range of temperature values. An alternative method to obtain the equilibrium moisture content is based on a device where the moisture content of the sample is known and a small volume of air reaches equilibrium with it. The device is a sealed container with a small volume of air. The sample is placed in the device and then the relative humidity of the air at equilibrium is measured. Electronic sensors are available for relative humidity measurement, but none can approach the accuracy required, particularly at low relative humidity, or be used at temperatures over 60°C.

There are few methods for measuring the humidity of air at drying temperatures. One uses a modified wet bulb psychrometer (Rocha & de Faria, 1992) but, as the instrument modifies the air, it is not suitable for this application. The only method remaining is dewpoint metering; recent developments have extended the range of conditions under which measurements may be made up to dry bulb temperatures of 95°C and to a maximum dewpoint depression of 40°C. This instrument (Protimeter DPS515) was employed in the current study.

The apparatus for equilibrium relative humidity determination is shown in Fig. 2.1. The sample was placed in a steel sample container, with a stainless steel mesh thimble maintaining adequate air space in the centre at the top for the dewpoint sensor. Apart from the space for the sensor, the container was filled as full as possible with the sample. The container lid, into which the dewpoint sensor was fitted, was then screwed on to the top of the sample container, with the threads sealed with polytetrafluoroethylene (ptfe) thread tape. The whole sample container was placed in a precision temperature controlled oven (stable to better than 0.1°C) at ambient temperature. The volume of air in the sample container was approximately 1/50 of the volume of tea, so that any change in moisture content of the air had negligible effect on the moisture content of the sample.

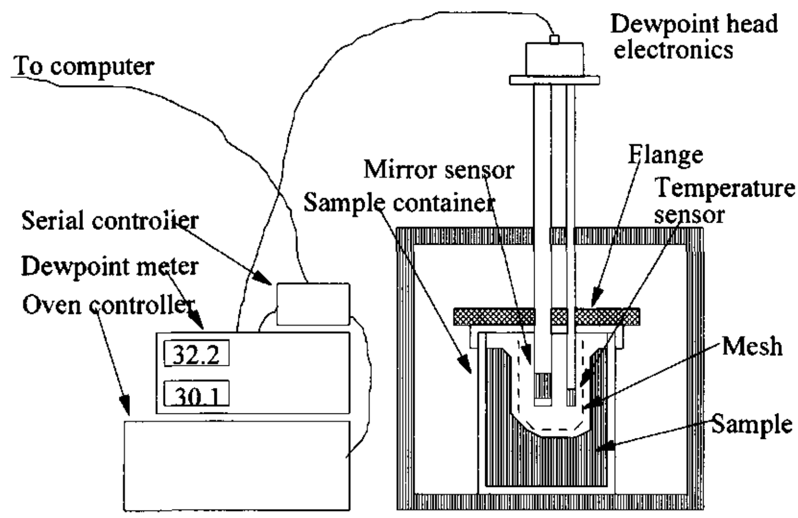

Fig. 2.1. Schematic diagram of the equipment for fast determination of equilibrium moisture

The dewpoint meter took readings of air temperature and dewpoint temperature, then calculated values for relative humidity on a cycle time of about 90 s; a computer logged these values via the serial port and a custom program monitored and recorded the values. To avoid the effects of pressure influencing the dewpoint measurement, the sample container was equipped with a narrow bore vent tube, connected to a length of plastic tubing outside the oven. The tube was long enough so that any water vapour lost from the sample chamber was condensed in the tube and was not lost to the system. The plastic tubing was approximately 1mlong, with the end section folded back on itself to form a seal.

To obtain readings at varying moisture, samples were taken from a continuous flow fluidized bed dryer. Once a sample was taken, it was placed in a sealed container of approximately twice the volume of the sample. It was allowed to equilibrate for at least two h, with frequent mixing, to ensure even distribution of moisture. Samples were then taken for moisture analysis using electronic moisture balances that had previously been calibrated against the standard oven method. At least three moisture determinations were made; if three agreed to within 0.1% moisture, no further samples were taken. If there was greater deviation, more samples were taken. This was particularly necessary for the wetter samples because the high drying rate in the dryer made taking a sample of uniform moisture content more difficult.

Following several trials, it was determined that if there were 20 readings with identical values for relative humidity (*i.e.* a stable period of 30 min), subsequent readings would not change by more than 0.1 percentage point relative humidity providing the temperature was stable. This was the maximum resolution of the dew point meter, so the criterion for equilibrium was adopted as 20 identical readings taken consecutively. Once the computer had logged these 20 identical readings, it sent a signal to the oven controller to increase temperature by 5 or 10°, depending on the controller setting. The computer would then wait for another 20 identical readings. Once a temperature of 95°C was reached (the dewpoint meter limit), the oven temperature would ramp no further, and manual intervention was required to terminate the test. The duration of a test was in the region of 24 h, which was not long enough for fungal growth to develop. During each test, data were collected equivalent to at least 15 experiments using the saturated salt method.

Initially, a reducing temperature ramp was also used to determine the extent of any hysteresis effect, and on early runs the values were found to be significantly different to the rising temperature regime, but erratically so. This was eventually tracked down to moisture leakage from the sample container at high temperatures, when there is a high vapour pressure gradient between the sample container and the air in the oven. Once this problem had been fixed, using high temperature silicone sealant where the probe entered the sample chamber, no difference was found between the increasing temperature tests and the decreasing temperature tests; the decreasing temperature regime was no longer used as no hysteresis for temperature could be detected. As this method only required minute transfers of moisture between sample and air, no significant sorption or desorption took place so no hysteresis would be expected.

Table 2.1 Saturated salts used for equilibrium moisture experiments; values taken from Wexler (1993)

Salt	Relative humidity, %
Sodium hydroxide $NaOH.H_2O$	6
Potassium acetate $KC_2H_3O_2$	13
Potassium carbonate $K_2CO_3.2H_2O$	44
Magnesium acetate $Mg(C_2H_3O_2)_2$	65
Ammonium sulphate $(NH_4)_2SO_4$	81
Zinc sulphate $ZnSO_4.7H_2O$	95
Copper sulphate $CuSO_4.5H_2O$	98
Lithium chloride $LiCl.H_2O$	11

As the instrument used could not handle dewpoint depressions greater than 40°C, the values at the low moisture end of the measurement range were evaluated by the saturated salt method. At these moisture contents below 5% w.b., fungal growth was not a problem. Several samples were placed in open sample tins in sealed dessicators, each of which contained a tray with the saturated salt. At weekly intervals, the solutions were checked to ensure that both crystals and liquid solution were present in the tray; if either was low, that component was topped up. After a month one of the samples from each dessicator was tested for moisture content, and this procedure was then repeated at weekly intervals until no more change could be detected. The salts used were AR grade, and are listed in Table 2.1.

2.4 Results

The data shown in Fig. 2.2 were obtained from saturated salt experiments at an average room temperature of 25°C, using unsorted (dryer mouth) teas from the production line of the Manufacturing Research Facility at Tea Research Foundation (Central Africa). Results from other workers are also shown in Fig. 2.2 for comparison.

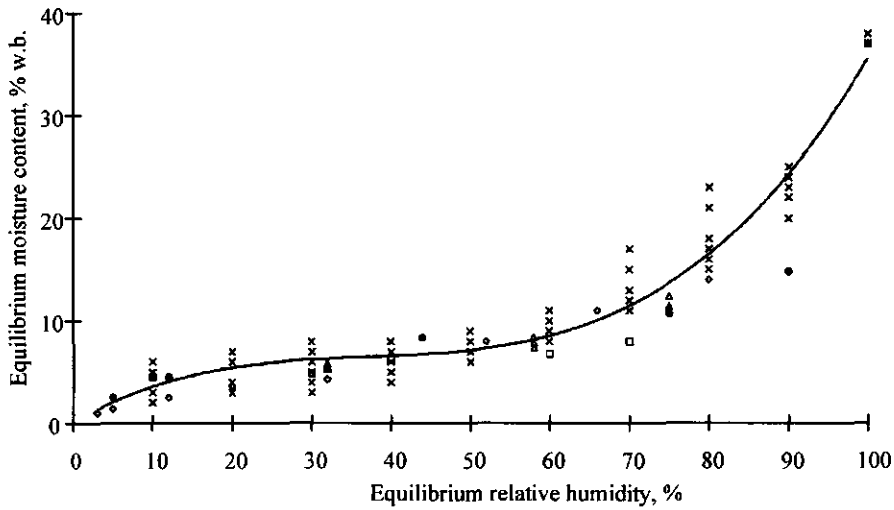

Fig. 2.2. Comparison of equilibrium moisture content values from this and other work, by the saturated salt method, taken at between 15 and 35°C. A polynomial fit is shown to all the data points combined. ***× Jayaratnam and Kirtisinghe (1974a); ◊ Jayaratnam and Kirtisinghe (1974b); Δ Dougan et al. (1974); □ Hampton (1992); • this work***

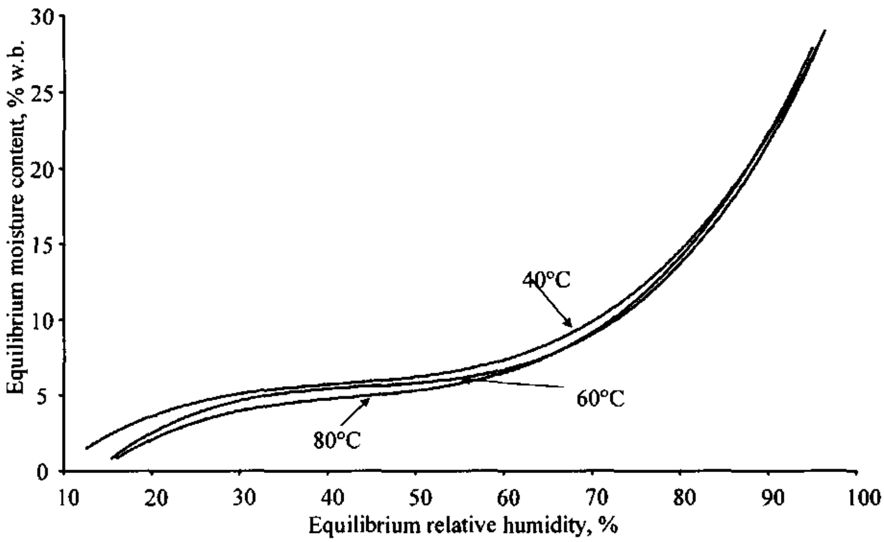

Fig. 2.3. Equilibrium moisture isotherms from dewpoint meter data.

Fig. 2.3 shows the results from the dewpoint meter studies as three isotherms, each representing over 90 data points. The difference between the 40°C and 60°C isotherms is greatest below 20% ERH and between 50 and 80% ERH, and least between 30 and 50% ERH and over 80% ERH. Between the 40°C and 80°C isotherms, the difference is consistent up to 75% ERH, and decreases above that value. As the relationship here is clearly not uniform, it is not possible to define a temperature dependency of the isotherms.

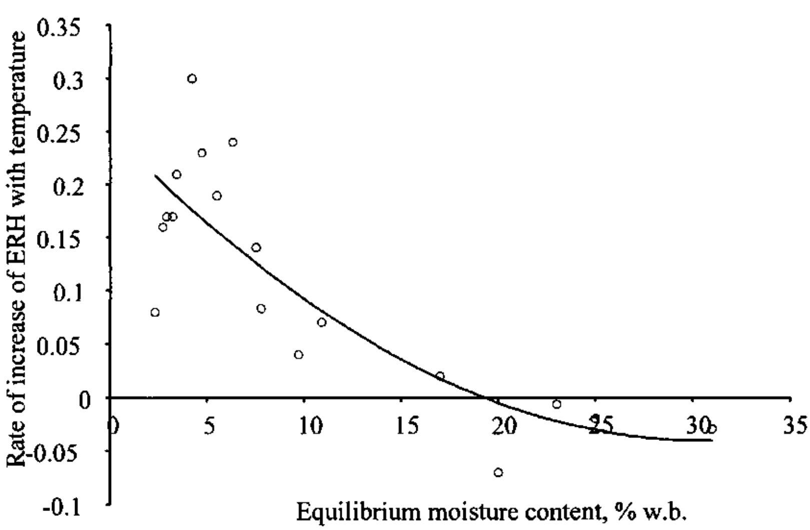

Fig. 2.4. Rate of change of equilibrium relative humidity with temperature as a function of equilibrium moisture content.

The data were also analysed as the rate of change of ERH with temperature for each sample moisture content tested (Fig. 2.4). Although there is a visible trend of decreasing rate of change with increasing moisture content, the relationship is not well defined.

Fig. 2.5 compares the values of ERH, averaged over the whole temperature range from the dewpoint meter method with the average values for all workers using the saturated salt method. Both methods give comparable results, with the dewpoint meter indicating lower moisture content for a given relative humidity. Third order polynomial lines are fitted to demonstrate the trends for the two sets of data. The difference between the average below 60°C value and the average of all values is small enough not to make any difference in practice.

In Fig. 2.5, each point in the saturated salt data represents the average of all values reported by all workers at this relative humidity. On the dewpoint meter data, each point represents the average value for all temperatures for one experiment only.

Although in previous figures, polynomials were used to illustrate the data, it is important to test the fit of the data to more commonly used relations for equilibrium moisture content. Lomauro *et al.* (1985) report results for some equations fitted to data on agricultural produce including tea.

The coefficients *a, b*, and *c* were found which gave the minimum mean relative deviation and standard error of estimate.

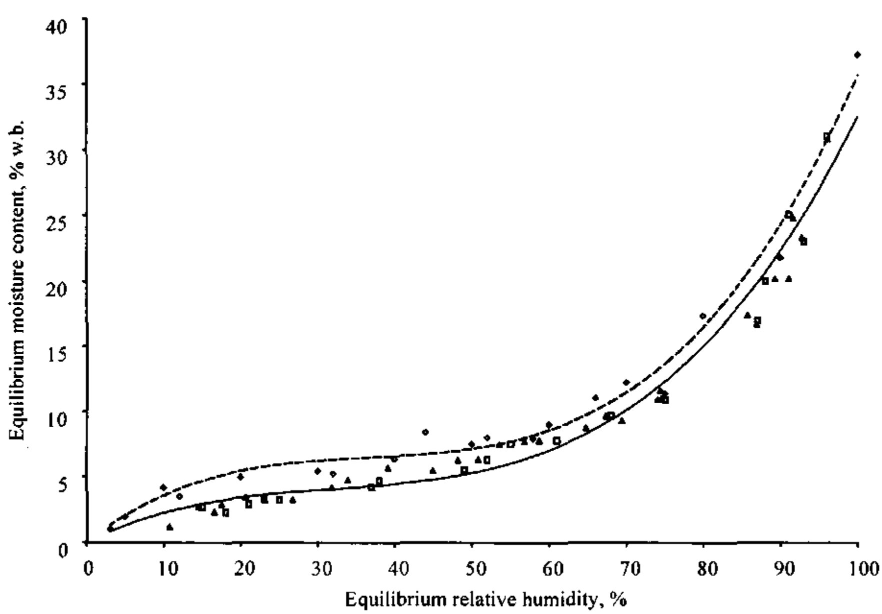

Fig. 2.5. Comparison of saturated salt method and dewpoint meter method, ---◊--- *saturated salt method; ——□—— dewpoint meter method.*

The Halsey equation (after Lomauro *et al.*, 1985):

$$M = \left(-\frac{1}{a}\ln a_w\right)^{-\frac{1}{b}} \tag{2.1}$$

where a_w is water activity.

The GAB equation [rearranged by Lomauro *et al.* (1985) after Bizot *et al.* (1983)]:

$$M = \frac{abc}{(1-cr_h)(1-cr_h+bcr_h)} \tag{2.2}$$

The Oswin equation (Oswin, 1946):

$$M = a\left(\frac{r_h}{1-r_h}\right)^b \tag{2.3}$$

The Henderson equation (rearranged from Henderson, 1952):

$$M = \left(\frac{\ln(1-a_w)}{a}\right)^{\frac{1}{b}} \tag{2.4}$$

Polynomial: $$M = ar_h^{\,3} + br_h^{\,2} + cr_h \tag{2.5}$$

Here, r_h is equilibrium relative humidity, M the moisture content wet basis and a, b, and c are constants depending on the material. The values for the constants and statistical error terms are shown in Table 2.2. Water activity a_w is equal to the relative humidity expressed as a decimal rather than a percentage.

Table 2.2 Constants and error terms in fitting of isotherm equations

Equation	Coefficient (a)	Coefficient (b)	Coefficient (c)	Residual sum of squares	Mean relative deviation	Standard error of estimate
Halsey	6.34	1.26		696.7	0.1402	6.599
Oswin	6.54	0.507		27.27	0.0962	1.306
GAB	6.71	0.4031	0.878	16.76	0.08072	1.023
Henderson	-0.123	0.957		23.47	0.1474	1.211
Polynomial	0.0000816	-0.00787	0.295	31.94	0.1162	1.413

In the Halsey, GAB and Oswin equations, the residuals were least at the low moisture end of the scale. The poor mean relative deviation values for the Halsey and Henderson equations are due to some large residuals with high moisture samples which did not occur with the other equations. Some bias was observed in the residuals for the Halsey equation. Fitting the same constants from the dewpoint meter data to the saturated salt data gave better standard errors for the Halsey, but slightly worse for GAB and Oswin (2.17, 1.77 and 1.97 respectively).

The results for the GAB model produce the best fit, followed by the Oswin model, as was also found by Lomauro *et al.* (1985).

As the standard method for moisture measurement in tea is an oven method (International Standards Organisation 1980) measuring loss in mass at a temperature of 100–105°C, any tea in equilibrium with air at over 100°C is defined as having zero moisture content. Thus the equilibrium moisture of tea with ambient air heated to over 100°C is zero.

2.5 Conclusions

These studies on unsorted (dryer mouth) tea extended the span of temperatures for equilibrium moisture values from ambient to the region of drying conditions. The change in characteristics with temperature was an effect which was not possible to quantify. The values over the range of temperatures tested obtained fell within the range of measurements by other workers using sorted teas at near ambient conditions. It is therefore valid to use the results found at ambient temperature for drying experiments, as any errors that might be introduced by this approximation are only minor.

Several of the equations commonly used to describe equilibrium moisture were fitted to the data. The Guggenheim-Anderson-de Boer and Oswin models gave slightly better results than a three term polynomial, but any of the three can be used to represent the results.

At the beginning of the study it was not known whether the results from near ambient experiments using the saturated salt method on sorted teas of various origin could be used for drying conditions. Either the dewpoint meter data or the saturated salt data from the average of all workers can be used for drying studies; the dewpoint meter data are slightly preferable because the average temperature at which the readings were taken is within the range of drying operations.

A method for determination of equilibrium relative humidity over a range of temperatures has been extended and proven. Computer control has made it possible to carry out experiments more quickly.

It has not been possible to determine a consistent relationship for the effect of temperature on equilibrium relative humidity. Over a narrow range of conditions (below a moisture content of 10%) a temperature dependence can be seen, but this cannot be extrapolated to cover the whole range of conditions in this study.

2.6 *Acknowledgements*

This study was partly financed by European Union Stabex funds provided to the Tea Research Foundation (Central Africa) for a project on Automation of Tea Processing.

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3 Fluidization of Tea*

3.1 Abstract

This work characterises the fluidization parameters for tea particles. Relationships were determined for minimum fluidizing velocity, pressure drops across the bed and bedplate, and bed expansion. The different bedplate designs only affect the fluidization by the range of loads that fluidize well on each bedplate. The values determined in this study can be used for design, operation and control of tea dryers. Limitations on the range of permissible air velocities and bed loadings were determined.

3.2 Introduction

Many tea factories have changed from endless chain pressure dryers to continuous fluidized bed systems for drying the fermented tea particles (dhool). Although many of these systems appear to work satisfactorily, there is no published data on the fluidization characteristics of tea required for design of such dryers and for their control.

A fluidized bed requires correct setting of airflow to operate without some material remaining static on the bed, and without excessive elution of light materials. Commercial tea dryers appear to operate with excessive airflows, as material is jetted well above the bed, which induces back and forward mixing of the particles. The objective in a commercial continuous fluidized-bed dryer is to approach plug flow as closely as possible, so any back and forward mixing should be avoided. Back-mixing causes excessive retention times well above the average, and forward mixing results in wet particles being delivered with retention times below average. If fluidization is not even, then mixing of the hot air and dhool is uneven, resulting in inefficient use of the air.

In the published work on fluidized bed tea drying, Kirtisinghe (1974) brings only a general view of the original development. Shah and Goyel (1980a) make no attempt to analyse airflow in one paper, and in another the authors (Shah and Goyel 1980b) show a simplified diagram of airflow and its abrasion effects. None of the papers addresses the problem of air quantity. For optimum tea quality, the fluidized bed should be arranged such that the residence time is a minimum, and that mechanical abrasion resulting in loss of "bloom", the fine leaf hairs on the surface particle, is minimized also.

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The objective of this study is to determine the requirements for fluidization of tea, for dryer design, operation and control. The main variables to be determined are the minimum fluidizing velocity u_{mf}, and the velocity at which elution of the light fraction of particles becomes unacceptable. Also the bed pressure at minimum fluidizing velocity may be determined.

3.3 Method and apparatus

The method and measurements to be taken are described by Kunii and Levenspiel (1991). They describe the use of a diagram of pressure drop against air velocity to determine the minimum fluidizing velocity. Before the onset of fluidization, air pressure drop across the bed material (not the bedplate) increases linearly with velocity. After fluidization starts, the pressure across the bed only rises at a small fraction of the rate before fluidization. With a uniform particle size distribution, the transition is distinct but is less well defined with a wide range of particle sizes. From the data gathered, the pressure at minimum fluidizing velocity can also be determined. Additional data on bed depth can then be used to determine the bed expansion, or the effective bulk density. This tends to increase very rapidly once the material comprising the bed starts to be eluted out of the top of the apparatus.

A test rig was constructed with a square bed plate of size of 270 mm x 270 mm (Fig. 3.1). Some features not essential for these experiments were incorporated to allow for other experiments. They were incorporated at this stage to ensure that the air flow distribution was uniform for both studies. A centrifugal fan provides the air supply, drawn from ambient air. An electrical actuator, under either manual control or feedback control from an airflow sensor, operates a sandwich valve. A venturi is used to increase the air velocity to the range acceptable for the flow sensor.

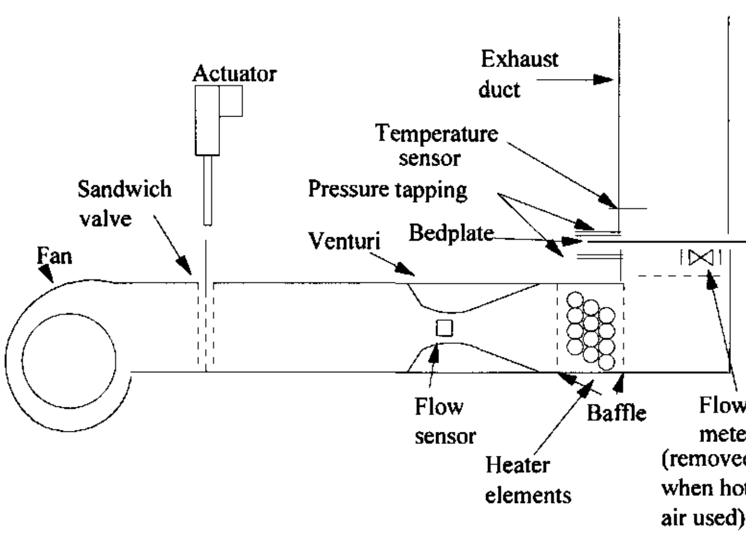


Fig. 3.1. Fluidization and batch drying test rig

In fluidization experiments, a parallel-sided duct was fitted above the bedplate, so that a constant air velocity would be maintained. The bedplate was designed to be changed quickly, and the exhaust duct could be hinged backwards for removal of tea samples from the bed. Pressure tappings were fitted immediately above and below the bedplate. An electronic air flow meter rotating vane sensor head was installed just below the bedplate to determine superficial velocity and to calibrate the flow sensor at the venturi. The vane sensor was removed when heated air was used. An electronic manometer, checked against a conventional manometer, was used to record pressures. In fluidization experiments no vibration of the bedplate or agitation of the sample was used, unlike some commercial dryers. Baffle plates of perforated metal were used to ensure even distribution of airflow over the area of the bedplate. Measurements at different locations on the bedplate demonstrated that the difference in air flow rate was less than 0.1 m/s at a nominal superficial velocity of 1.0 m/s. This was the maximum precision available from the instrumentation (±0.05 m/s).

The airflow sensor was calibrated to produce readings corresponding to the superficial velocity at the bedplate.

3.4 Experiments

The airflow resistance characteristics of four types of bedplate typically used in commercial tea dryers were determined by experiment. The data from these experiments were then used to determine pressure drop across the bedplate during fluidization experiments, then subtracted from the total pressure drop over the bedplate and tea.

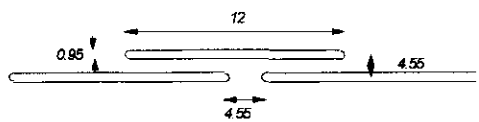
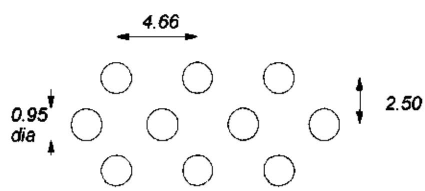
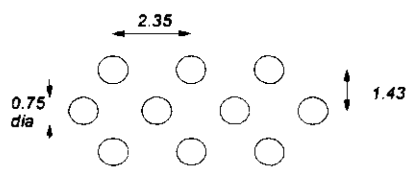
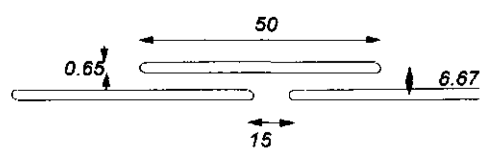
In all fluidization experiments, samples of black tea were taken from the dryer discharge of the pilot scale continuous production lines at the Tea Research Foundation (Central Africa) Manufacturing Research Facility. Standard Lawrie Tea Processor (L.T.P.) manufacturing procedures were observed, using withered leaf of with a moisture content of approximately 71% w.b., fermenting time of approximately 50 min on clonal teas and 90 min on seedling teas. Representative samples were analysed for particle size analysis using standard sieves. Bed loading was recorded as kilograms of tea per square metre of bedplate.

For each bedplate in turn, a sequence of increasing bed loads was tested to determine minimum fluidizing velocity. The lowest bed loading found on a continuous dryer in practice was around 6 kg/m^2, so the starting value was taken as half this and increased by 3 kg/m^2 steps up to a maximum of 18 kg/m^2, and then further readings at 6 kg/m^2 steps to 42 kg/m^2 where it was impossible to obtain full fluidization.

The correct amount of dry tea was weighed into a tared container, and tipped down the exhaust duct (Fig. 3.1) with the fan on, but the air valve closed. The air valve was then opened just enough to fluidize the sample, then closed again. This was to ensure that the run was started with a level bed.

The zero readings on the airflow meter and the micromanometer were then checked before the run itself was initiated. The air valve was opened very gradually until a small stable airflow could be measured. The flow and pressure were recorded and an estimate of bed depth, and the air valve opened again slightly. A sequence of readings of superficial velocity and pressure across the bed and bedplate was taken until the point where the tea particles began to elute. The final reading was taken as quickly as possible before a significant portion of the bed load had been eluted.

Table 3.1 Geometric parameters and coefficient of resistance to airflow *k* for four bedplate types.

No	*Material thickness, mm*	*Open area*	*Opening type and dimensions, mm*
1	Steel 1.9	Slot 12 mm x 0.95 mm = 11.4 mm^2 Plate 4.55 mm x16.55 mm = 75.3 mm^2 Open area = 15.1% Coefficient k = 48 Ns^2m^{-4} Land 3.6 mm x plate length or 4.55 mm x 8.15 mm	
2	Steel 0.95	Hole 0.95 mm dia. = 0.709 mm^2 Plate 2.18 mm x2.50 mm=5.44 mm^2 Open area = 13% Coefficient k = 31 Ns^2m^{-4} Land 1.55mm x 3.3 mm or 4.05mm x 1.23mm	
3	Steel 0.55	Hole 0.75 mm dia.= 0.44 mm^2 Plate 1.33 mm x1.163 mm=1.55 mm^2 Open area = 28.3% Coefficient k = 6.0 Ns^2m^{-4} Land 0.58 mm x 1.58 mm or 1.91 mm x 0.41 mm	
4	Aluminium 2.0	Slot 50 mm x 0.65 mm = 32.5 mm^2 Plate 65 mm x 6.67 mm = 434 mm^2 Open area = 7.5% Coefficient k = 91 Ns^2m^{-4} Land 6.0 mm x plate length or 15 mm x 13.7 mm	

Below fluidization velocity, the bed depth was estimated to the nearest 5 or 10 mm but, once full fluidization had been achieved, it was difficult to estimate the bed depth with an accuracy of closer than 50 mm as the top of the fluidized material was not well defined. Notes were taken on the state of fluidization of the bed.

From the graph of pressure drop across the bed against air velocity, the onset of fluidization was determined manually for each trial. In some cases there was no clear transition visible at all.

3.5 Results and discussion

The airflow resistance properties and other data for the four bedplates are summarised in Table 1. A value for resistance to airflow was determined by plotting pressure drop against air velocity for individual plates. The relation found was that the pressure drop Δp across the bedplate is proportional to the square of the velocity u: $\Delta p = ku^2$, where k is a constant. A relationship of this form is expected from Bernoulli's theorem. In all cases, the coefficient of determination R^2 was better than 0.987 and the standard error of the slope was better than 1.75 % of the slope value. The value k for each bedplate is quoted in Table 3.1, where pressures are in Pa and velocity u in m/s.

For the determination of minimum fluidizing velocity as described by Kunii and Levenspiel (1991), the mean particle size of the teas used was 0.84 mm. The moisture content of the tea used was in the range of 8-10% w.b., being in equilibrium with the ambient air used for the fluidization tests. An example of the plot of pressure drop across the bed against air velocity is shown in Fig. 3.2 for bedplate number 2 for the lower part of the loading range. The results for the other bedplates showed a similar pattern. The minimum fluidizing velocity determined from the point of inflection on these graphs according to Kunii and Levenspiel (1991) is shown in Table 3.2. Where no figure is shown there was either no distinct transition or no effective fluidization.

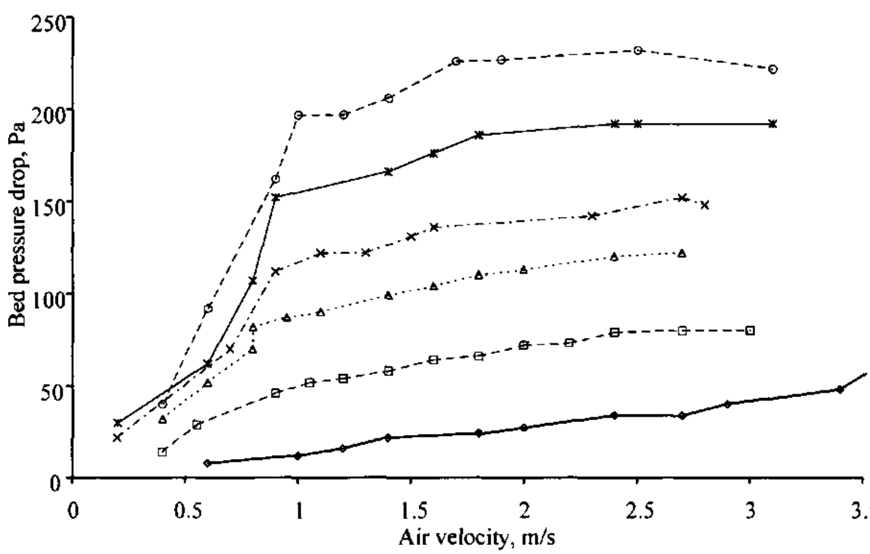


Fig. 3.2. Variation of pressure drop across bed with air velocity for bedplate 2 and indicated bed loads; *—◇—3 kg/m²; --□-- 6 kg/m²; ···Δ··· 9 kg/m²; -·-x-·-12 kg/m², ——*—— 15 kg/m²; –o—18 kg/m²*

Table 3.2 Minimum fluidizing velocity in m/s for varying load on four different bedplate types.

Load, kg/m^2	Fluidizing velocity, m/s			
	Plate 1	Plate 2	Plate 3	Plate 4
3	-	-	-	1.0
6	1.0	-	-	1.1
9	0.9	0.9	0.9	1.1
12	1.0	1.0	1.0	1.2
15	0.5	1.0	1.0	1.1
18	0.6	1.0	1.0	1.2
24	0.5	0.5	0.8	0.60
30	0.5	0.4	-	0.45
36	0.6	0.35	-	0.50
42	0.7	-	-	0.40

Where good fluidization was attained, the value for minimum fluidizing velocity was between 0.9 and 1.2 m/s. As bed loading increases beyond a certain point, a lower value is found. This is the result of channelling. When channelling occurs, there are regions of the bed which are not fluidized at all, and channels between these regions where fluidization is occurring. Therefore the mean superficial velocity as measured will fall, although the velocity in the fluidized channels will be high and over the rest of the bed it will be low. In commercial dryers, channelling may not be detected visually as the surface of the bed still appears to be moving; it is the layers below which are not fluidized. If non-fluidized material is permitted to reside on the bed, the residence time of this material will be much more than the mean residence time and product quality will suffer. The reduction in mean superficial velocity as channelling occurs may be used to detect the onset of channelling; however a restriction in weir height leading to a lesser depth of bed would achieve the same effect more simply.

Taking the values of pressure drop at which minimum fluidizing velocity is attained from the same graphs and plotting this against the bed load, the relationship shown in Fig. 3.3 is obtained.

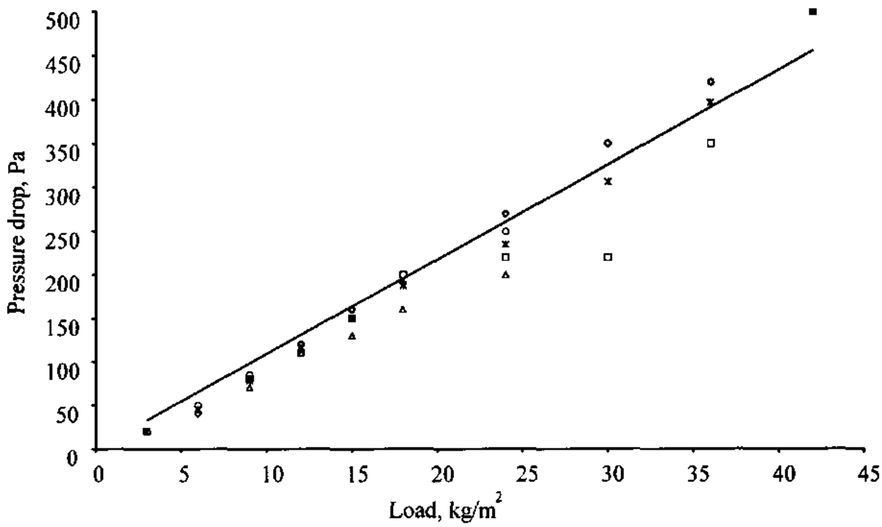


Fig. 3.3. Pressure at minimum fluidizing velocity for four types of bedplate, with a regression line fitted to the mean values and passing through the origin; ***◊, plate 1 slotted with 15% open area; □, plate 2 drilled with 13% open area; Δ, plate 3 drilled with 28% open area; o, plate 4 slotted with 7.5% open area; * mean of four plates.***

As the pressure drop across the bed was not measured directly, but by difference from the drop across the bedplate and fluidized material, this shows a good approximation to a straight line. Regression analysis, forcing a linear regression with an origin of 0,0 gives a coefficient of determination R^2 of 0.980, and yields an expression $\Delta p = 10.86M$ (where M is the bed load in kg/m^2), with a standard error for slope of 0.30.

For bed expansion, the actual values of expanded bed height in mm were divided by the bed loading rate to obtain a value independent of load. This is effectively the reciprocal of the bulk density of the bed.

As the values for bed height were very difficult to determine accurately above minimum fluidizing velocity, all data have been pooled; Fig. 3.4 shows the results. Regression lines have been fitted separately to the data above and below 1.1 m/s superficial airflow, representing bed depth when fluidized and not fluidized, respectively.

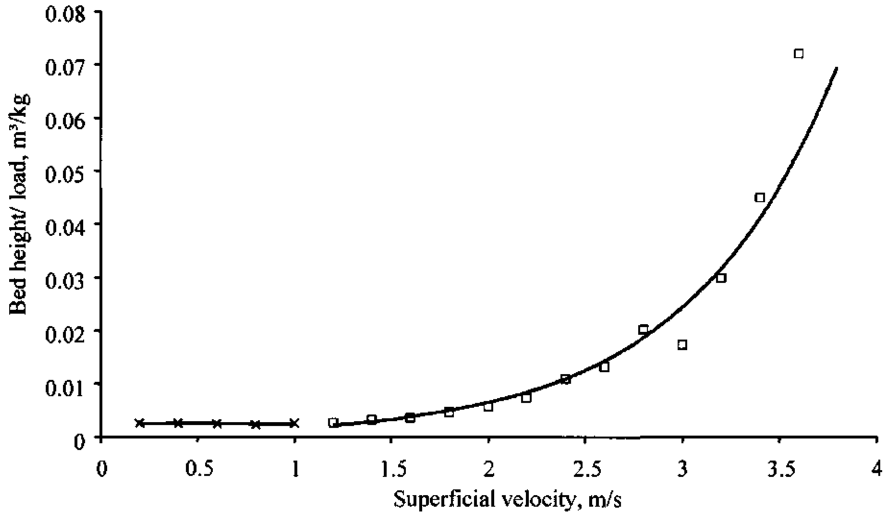


Fig. 3.4. Variation of bed expansion against superficial velocity; × *non-fluidized;* □ *fluidized*

Before fluidization occurs, there is a constant bed height of 2.5 mm per kg/m^2 of load. After fluidization, the bed expands according to the relationship:

$$l = 0.46w.e^{1.32u}$$

where l is the expanded bed height in mm, w the load is in kg/m^2 and u is airflow in m/s.

These results only apply to dry teas. An attempt was made to make measurements on undried tea dhool, at a moisture content of around 72% w.b., using the same apparatus, but the material lost water so rapidly even with ambient air that the moisture content was not stable during measurements. However, it was obvious that higher moisture teas require a greater airflow.

An alternative was to make measurements on a continuous dryer operating at steady state, which takes dhool at a moisture content of 68-74% w.b. and discharges at about 3% w.b.. Measurements on a continuous fluidized bed dryer are very difficult, as the inlet temperatures are higher than the instruments are able to handle, and above bed measurements are made difficult by the light fibre being eluted. The best measurements obtained were 1.3 m/s at the wet end of the dryer (moisture content of 72-40% w.b.), 1.1 m/s in the middle (moisture content of 40-10% w.b.) and 0.9 to 1.0 m/s at the dry end (10-3% w.b.).

From the rapid bed expansion displayed in Fig. 3.4 after the onset of fluidization, even the average sized particles will be eluted at an air velocity in the region of twice the value of u_{mf}. As the bed is made up of a non-uniform distribution of particles, the lighter ones will elute at even lower velocities; in experiments with dry tea some fibre may even be eluted before the onset of fluidization. It appears that the airflow requirements are set in a narrow band for a given moisture of tea, requiring a constant volume delivery from the fan. Unfortunately the fan characteristics will not yield a constant flow rate when the load (or pressure) fluctuates. During normal operation the load on a fluid bed dryer should not vary significantly, but the back pressure from the bed will vary when the dryer is being started with no bed load. Fluctuations in supply voltage to the fans can cause further disturbances.

In an attempt to maintain the constant airflow required, a controller was implemented on a continuous-flow-fluidized-bed dryer, sensing airflow between the fan and the heater unit. This was found to work well when tea of a consistent moisture content was being fed to the dryer, but if the moisture content varied by over three percentage points wet basis from normal then manual adjustments had to be made. It would be better to detect fluidization directly, and regulate the air to achieve the correct amount of movement of the tea.

In a feasibility study on alternative methods for regulation of fluidization, both ultrasonic and optical (laser) sensors were evaluated, and found to be able to detect fluidization. The ultrasonic sensor detected movement of the surface of the bed, and the optical sensor detected intermittent occultation at just above expanded bed level. However a more sophisticated form of regulation is needed, because the same signal came from the sensor when no tea was present (less air required to avoid elution of fresh feed) or when tea was present but not fluidized (more air required to achieve fluidization). The ultrasonic system was not sensitive enough to determine the depth of tea on the bed, using a frequency in the 40 kHz range; higher frequencies would provide improved resolution but may penetrate the top of the bed, and fail to detect fluidization. Further work is required to develop an automatic airflow control system, which might combine a fluidization detector with a flow measuring sensor. The flow would be kept within limits from the flow sensor, but modulated within those limits by the fluidization detector.

As the air velocity requirements are dependent on dhool moisture content, it might be possible to use a moisture measurement to determine the correct setting. Attempts were made to calibrate two types of near infrared (NIR) reflectance moisture meters. A good calibration was achieved below a moisture content of 15% w.b., but sufficient accuracy could not be attained for dhools with a moisture content of about 72% w.b. over variations in fermenting time and plant cultivar.

It might be possible to use the relationships determined in this study for the pressure drops across the fluidized bed, the non-fluidized bed and the bedplate, together with the relationship for expanded bed height and effective bulk density, to determine the onset of channelling. Fluidization stability is important to maintain plug flow of material through the bed, so if it were possible to model stability in terms of bedplate design, weir height, and other variables then designers of fluid bed dryers could investigate the limits to fluidization.

3.6 Conclusions

For four types of bedplate with dry tea, the minimum air velocity for fluidization was determined to be between 0.35 and 1.2 m/s. Elution of light particles was observed soon after the onset of fluidization, reducing the acceptable airflow velocities into a narrow range.

Measurements on an industrial dryer showed that slightly higher air velocities were required for tea at higher moisture contents; an air velocity of 1.3 m/s with the tea at a moisture content of 72% w.b. being required for normal operation, falling to 0.9 m/s at 3% w.b.

The experiments showed a dependence of the pressure drop across the layer of the fluidized material at minimum fluidizing velocity to be linearly related to bed load. The bed expansion is also a linear function of load and an exponential function of the airflow velocity.

Bedplate variables were also found to influence the stability of fluidization. A smaller open area percentage allowed fluidization over a wider range of bed loadings. The pressure drop across the bedplate was found to vary with the square of velocity. Limits to fluidization were found at higher bed loadings, when channelling occurred.

3.7 Acknowledgements

This study was partly financed by European Union Stabex funds provided to the Tea Research Foundation (Central Africa) for a project on Automation of Tea Processing.

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4 The effect of drying on black tea quality*

4.1 Abstract

Drying is an important part of tea manufacture, where enzymic reactions in earlier phases are terminated by heat and moisture loss, and new compounds are produced by the action of heat. This work is an attempt to quantify the temperatures required to produce the desired changes without damage through exposure to excess heat. Experiments were carried out giving already dried tea further heat exposure, drying tea from wet dhool in a thin layer, and drying a larger sample in a batch fluidized bed dryer. Temperatures in the range of 60°C to 140°C were tested. Effects were monitored by commercial tasters, thin layer chromatography, reversed phase and size exclusion chromatography. Exposure to at least 80°C was found to be necessary for quality development. For periods of less than a minute, tea particle temperatures of up to 120°C may be tolerated but in general temperatures of 110°C and above may be considered deleterious. Inlet air temperatures may be in excess of these values but only while drying rates are high. The stewing phenomenon, cited by several authors, could not be found when drying times of less than 15 min were used.

4.2 Introduction

During the manufacture of black tea from the young shoots of *Camellia sinensis*, compounds conferring colour and flavour are generated by enzymic oxidation of the flavan-3-ols and subsequent reactions, including coupled chemical oxidations, of the active intermediates generated (Robertson 1992). When the desired quality has been reached, drying is used to halt the reactions. Chemical change is not instantaneously arrested, but initially accelerated by the increase in temperature until the enzymes are inactivated by water removal or denatured by heat. Enzyme destruction is essential to stabilise the product in storage (Stagg 1974; Cloughley 1981; Dougan *et al.* 1979).

During the drying process other chemical changes occur, under the driving force of heat rather than enzymic action which may be detected by the human senses, but which have not been identified or chemically defined yet. Some of these changes are desirable, others are deleterious to quality. Once the free moisture has been removed, i.e. the tea is 'dry', further exposure to heat will raise the particle temperature to a level where quality loss and a burnt taste start to appear. Drying is therefore a critical step in the manufacturing process.

Control is necessary not only to preserve and promote quality, but also to minimise energy inputs and to maximise factory throughput. The end point of the drying

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process is normally 3% moisture content wet basis. Note that moisture contents in the tea industry and in this paper are expressed as wet basis, i.e. $100 \times \frac{\text{mass of water}}{\text{total mass}}$.

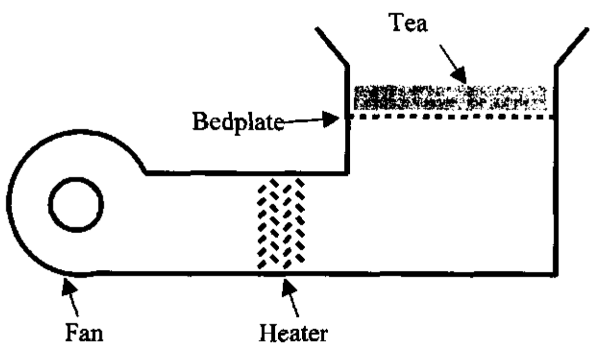

Fig. 4.1 Basic dryer

A tea dryer consists of a means of supporting the tea (bedplate) and a means of forcing hot air through the mass of tea (fan and heater) (Fig. 4.1). If the air flow rate causes the tea to rise just above the bedplate and become like a fluid, then it is termed a fluidized bed dryer. In Malawi where continuous processing has been adopted, dryers are fed with a steady flow of wet dhool and continuously discharge dry tea. In a commercial fluidized bed dryer, it is common for the first stage of drying to have an inlet air temperature of 120-140°C, and the final stage to be at 90-100°C.

Research on tea processing has been limited by the availability of objective measures of tea quality. Few liquor components have been identified, or may be quantitatively assayed. It is also suspected that there are complex interactions between components affecting their colour and flavour expression (Sanderson *et al.* 1976; Millin *et al.* 1969; Powell *et al.* 1992). As analytical techniques have developed, models of quality have been proposed (Roberts & Smith 1963; Owuor & McDowell 1994; McDowell *et al.* 1995). As well as subjective assessment by tea taster using commercial techniques, chromatographic techniques are used in this study to estimate the precursor flavan-3-ols, their derivatives the theaflavins, which contribute to colour and briskness, and thearubigins that make up much of the colour. The same technique simultaneously estimates caffeine, which modulates the expression of flavour of theaflavins and thearubigins (Sanderson *et al.* 1976; Millin *et al.* 1969), and is presently of interest to consumers for its pharmacological effects (Marks 1992). It is known that enzyme activity, temperature and time influence change in the relative amount of these compounds. Those compounds that can be identified and quantified will be used as markers of chemical change, although it is acknowledged that the sensory changes may be attributable to other unidentified compounds.

Previous work (Temple & van Boxtel 1999a) demonstrated that the airflow could not be used as a control input for a fluidized bed dryer, as the range which provides good fluidization is very narrow. The only alternative to airflow is air temperature; the objective of this paper is to determine the range over which air inlet temperature can be varied without adverse effects on product quality.

The approach in this study is to first determine how much additional heat exposure can be sustained by already-dry tea, before any deleterious effects can be detected. Following that, the effects of various drying regimes on quality should be determined.

4.3 Materials & methods

4.3.1 Heat exposure of already dried black tea

All samples were taken from the same, well-mixed bulk of graded (PF1 grade) tea dried commercially, that had been exposed to a maximum particle temperature of 90°C. This eliminated any differential effect due to the initial stages of the drying process from this experiment. Samples were subsequently exposed to hot air at different temperatures for different amounts of time in a bench-top fluid bed dryer (Sherwood Scientific). Air temperature was measured in the bed using a thermocouple probe and digital thermometer. No significant drying took place; the dryer was used purely as a source of hot air in this experiment. The control can be zero extra heat exposure, as no loss in perceived quality may be tolerated.

The dryer was allowed to stabilise at a constant temperature and an airflow near minimum fluidizing conditions for the sample, then the sample, at approximately 30°C, was introduced. For the shorter exposure times, the temperature of the tea surface did not reach inlet air temperature until a significant part of the total exposure time had elapsed, because of thermal inertia. In these cases, the exhaust temperature half way through the exposure time was taken as the mean tea temperature.

Exposure times of 1, 2, 4, 8, 16, 32 and 64 min were used. At the higher temperatures only the shorter times were used, and at the lower temperatures the 1 and 2 min samples were not taken.

After exposure, the heated sample was packed into a foil sample bag and left open until it had cooled. Sample size was 40-50 g. Samples were assessed by blind tasting by a commercial tea broker. Three controls were included, randomly inserted between the other samples. The samples were labelled as a drying experiment, and assessment for drying faults was requested. Valuations were expressed in US cents per kg.

4.3.2 Non-fluidized thin layer drying

Thin layer drying can ensure that each particle is exposed to as near identical conditions as possible and continuous monitoring of bed weight gives moisture monitoring in real time.

Apparatus[†] built for thin layer drying studies (Temple and van Boxtel 1999b) was employed. It has a measured air supply with a regulated temperature up to 140°C. The bed area is 0.058 m^2. The bed load of 72 g dhool used for the thin layer studies was increased to 102 g to ensure a large enough sample of made tea for analysis. Dhool was derived from clone SFS 204, withered overnight to 71% moisture, macerated by 3 passes through the research Cut, Tear & Curl (CTC) machine and fermented for 50 min at 21°C in a saturated atmosphere.

The same airflow rate (0.095 m/s superficial velocity) was used for all trials and the inlet temperature was kept constant during a run. Duplicate runs at inlet temperatures of 60, 80, 100, 120 and 140°C were performed.

Before starting a run, the moisture content of the dhool was determined by infrared moisture balance (Ohaus MB200). The weighed dhool was spread evenly on the bedplate, which was then placed onto the apparatus, which was already at the correct operating temperature and airflow. The actual initial load was used to determine the balance reading that would give a final moisture content of 3.0% w.b. As soon as the balance reading reached this value, the run was stopped and the dry tea collected into a sealed sample tin for analysis. Inlet air temperature, airflow and sample weights were monitored at 20 s intervals throughout each experiment. Ambient temperature and relative humidity were recorded manually at the start of each experimental run.

4.3.3 Batch fluidized bed drying

A research batch fluid bed dryer described by Temple & van Boxtel (1999a) was used for quality experiments, with the end-point determined by moisture meter. The dhool was prepared as above.

Two groups of experiments were conducted. For the first group the inlet temperature was maintained at a constant value of 90, 100 or 110°C. For the second group the inlet temperature was held below a maximum value, but the inlet temperature was controlled by feedback from the exhaust temperature. While the exhaust temperature was below the predetermined value (settings of 90 and 100°C were used), the inlet temperature was set at the maximum inlet value (settings of 120 and 140°C were used). As the exhaust temperature approached its maximum set value, the inlet temperature was reduced by the control system to ensure that this predetermined maximum was not exceeded.

Airflow was controlled to maintain even fluidization as close to minimum fluidizing velocity as possible throughout the run. The bedplate was vibrated throughout the run at an amplitude of approximately 1 mm and a frequency of approximately 10 Hz.

[†] This and other apparatus for which no maker is identified was designed and constructed at the Tea Research Foundation (Central Africa).

The end-point of the experiment was determined by moisture measurement using a near-infrared moisture meter (Moisture Systems MicroQuad 8000) calibrated for tea. Two calibrations were used. One covered the range from 70% m.c. w.b. down to 2%, while the second calibration was specified for the range 10% to 1%. Over the narrower span a more accurate algorithm was possible. The values from the wide span calibration were logged to computer for progress information, while the narrow range value was used to stop the run as soon as the moisture content fell below 3.0%. Each treatment was duplicated.

For comparison with the standard in-house sample preparation method (Temple 1999), some samples were dried in a propane-fired tray dryer with an inlet temperature of 90-100°C, manually controlled, and a fixed drying time of 10 minutes.

Dry samples were immediately passed over a 2 mm and 160 μm sieve shaken on a mechanical shaker (Octagon) for 1 minute. The portion retained on the 160 μm sieve was exposed to an electrostatic fibre extractor to remove coarse fibre, and packed in foil-lined laminated paper sample pouches. Sorting facilitated cooling. Samples approximated to F1, the main grade marketed from Malawi.

A commercial tea broker tasted the made teas, and they were analysed by high performance liquid chromatography (HPLC) using both reversed-phase and size-exclusion columns.

4.3.4 Chemical Analysis

Reversed-phase HPLC (Temple & Clifford 1997)

Column; Hichrom H5ODS EXCEL C18 5 μm 250 × 4.6 mm (Hichrom, Theale, U.K.). Solvent A: acetonitrile. Solvent B: acetic acid 10 ml litre^{-1}. Gradient: Linear 8 to 31% A over 50 minutes, 10 minutes at 31% A, before returning to 8% A over 10 minutes. Fifteen minutes re–equilibration. Flow rate: 1.5 ml min^{-1}. Injection volume: 20 μl.

Size exclusion HPLC chromatography (Temple 1999) (SEC-HPLC)

Column: Phenomenex Biosep 2000 Column 300 × 7.8 mm, with 75 mm × 7.8 mm guard column (Phenomenex, Macclesfield, U.K.). Mobile Phase: Sodium dodecyl sulphate 1 g litre^{-1} Sodium azide 0.5 g litre^{-1} Flow rate: 1 ml min^{-1}.

Preparation of black tea liquor for RP-HPLC.

Black tea leaf (6g) infused with 250 ml boiling 0.002 M acetate buffer pH 5 for five minutes in a 500 ml Thermos vacuum flask shaken on a reciprocating shaker at 1 Hz. The liquor was filtered through glass wool, cooled by holding the flask under running tap water for two minutes.

Isolation of ethyl acetate-insoluble thearubigin-rich fraction (EAITR) for SEC-HPLC

Each black tea was soaked overnight in chloroform to remove caffeine and chlorophylls, then air-dried in a Buchner funnel. Black tea leaf (6 g) infusing 6 g with 250 ml boiling 0.002 M acetate buffer pH 5 for five minutes in a 500 ml Thermos vacuum flask shaken on a reciprocating shaker at 1 Hz. After filtration through glass wool the liquor was cooled to 65°C. The warm liquor was partitioned with four volumes of chloroform to remove any residual caffeine, then extracted with six volumes of ethyl acetate. The upper organic layer was discarded.

Chlorophyll residues (Harbourne 1982)

Black tea (5 g) was ground in a glass mortar with 8 ml acetone, the extract clarified in a benchtop centrifuge, and then the supernatant made up to 10 ml. The extract was streaked onto a cellulose MN 300 plate prepared in house using an applicator improvised by sandwiching two coverslips between two microscope slides. Therefore application was not quantitative.

Mobile phase: Hexane (60–80°C): acetone: n-propanol 90:10:0.45. The tank was protected from light. Separation occurred within 25 to 30 minutes. The plate was sandwiched between two plates of glass and scanned using Colourvision™ software immediately, as the pigments are labile in daylight.

4.4 Results and discussion

Table 4.1 Effect of exposure to elevated temperatures on taster's assessment.

Key to scores: 0=Clean, 1=bakey, 2=touch bakey, 3=high fired, 4=burnt, 5=very burnt. The grey shading shows the safe operating areas for exposure.

time min	**1**	**2**	**2.5**	**4**	**8**	**16**	**32**	**64**
Exposure temp °C								
140	3		5					
135	1		4					
130	2	1	2	2				
120	[illegible]	0	0	1	2			
110	[illegible]	0	2	0	1	2		
100	[illegible]	0	0	0	2	2		
90	[illegible]	[illegible]		1	1	2		
80					0	0	0	0
70					0	0	0	0

4.4.1 Heat exposure of already dried tea

The tasting results for the dry tea samples subsequently exposed to elevated temperatures were expressed as scores for various parameters, comments and values. Variation in normal tasting parameters was minimal. The comments were scored and are shown in Table 4.1. Because the tea had already been dried, and had been affected to some extent by heat already, no loss in quality could be tolerated, so the only acceptable value was zero.

Initial examination of the results expressed as valuations rather than scores showed a logarithmic relationship with time, so values were plotted on a graph of temperature and log of time in min (Fig. 4.2). The line drawn is a manual estimate of the constant value line at 100 cents.

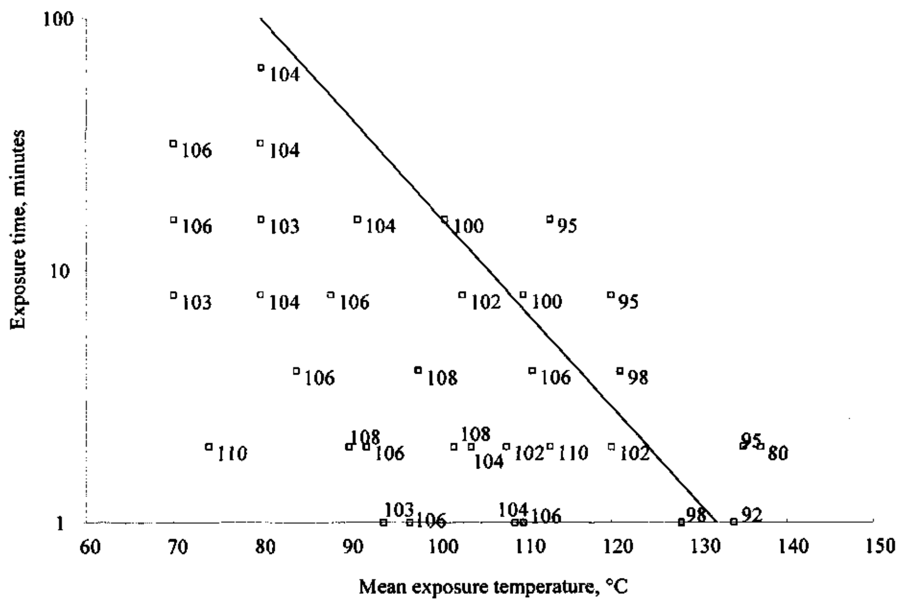

Fig. 4.2 Broker's valuation of tea samples exposed to heat for varying times and temperatures. Line divides values above and below 100 US cents/kg

Multiple regression analysis of value against $\log_{10}$ time and temperature yielded the following relationship:

$$V = 132 - 0.27T - (5\log t)$$

where V is value, US cents per kg, T is temperature, °C and t is time, min.

The coefficient of determination (R^2) was 0.56 with a standard error for value of 3.98 US cents/kg. This is a good result considering that the controls, which should have been identical, were valued at 112, 106 and 103, a standard error of 2.64 US cents/kg. This latter value indicates the variability of brokers' subjective assessments, but notwithstanding this, the data presented in Fig. 4.2 and represented by the equation above indicate clearly how product value can be lost by inadequate control of processing. The effect of exposure varies directly with temperature, but with the log of time, and while temperatures below 90 °C for extended periods have no detectable deleterious effect, a particle temperature of 120 °C for more than a minute should be avoided. For the tea studied, the established relationship implies that the value can never be greater than 132 US cents/kg.

4.4.2 Non-fluidized thin layer drying

Once the limits of exposure were determined by the previous trial, drying experiments working within these limits were carried out. Random motion within a continuous fluidised bed dryer makes the drying history of an individual sample of tea almost impossible to determine. The dryer used for thin-layer drying allowed the exact drying time to be known and sample identity to be maintained. The effect of different exposures to temperature during drying, rather than on already dry tea, was then determined.

The thin layer equipment provides the most consistent conditions to which a particle is exposed, but could only dry a small sample, limiting subsequent chemical analysis. The batch fluidized bed dryer has a less controlled drying rate (a constant rate period at the start of drying will slow the process) yet accommodated a larger sample size, at a close approximation to commercial practice.

To dry tea down to 3% moisture content, the humidity of the drying air must be below the equilibrium moisture content of tea at 3% moisture. With the lowest inlet temperature, 60°C, the target moisture content could not be achieved because relative humidity of the heated air was too high. As the end point in this experiment is determined by moisture content, the exposure time will bear an inverse relationship to temperature.

As few of the polyphenolic fermentation products are defined or assayable, chemical change is assessed by measuring residual pre-cursors, and known assayable products of fermentation.

Caffeine contents were higher at drying temperatures of 60°C and 80°C than at 120°C and 140°C (Fig. 4.3). As caffeine is lost from tea at a relatively low temperature, and is frequently found condensed on the cooler parts of commercial tea dryers with a maximum particle temperature of less than 100°C, this result was as expected; however at 100°C an anomalous low value was found. Caffeine is of interest because it affects expression of the flavour of theaflavins and thearubigins (Sanderson *et al.* 1976; Millin *et al.* 1969), and is presently of interest to consumers for its pharmacological effects (Marks 1992). Higher drying temperatures and shorter drying times produced higher levels of free gallic acid, which is present at higher levels in black tea than the growing plant, where it is present as esters. Galloyl esters are important to the flavour of polyphenolics (Ouwor & McDowell 1994; Clifford *et al.* 1996). As residual flavanol gallates and theaflavin gallates were not correspondingly reduced, it is assumed that the observed gallic acid was released from thearubigins with possible modulation of their sensory activity.

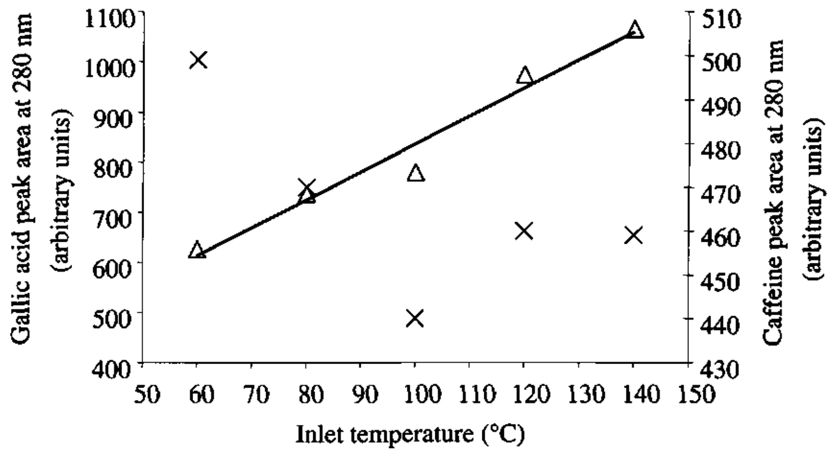

Fig. 4.3 Effect of increasing inlet air temperature on components of tea liquor, determined by reversed-phase HPLC monitored at 280 nm. Δ, gallic acid; ×, caffeine.

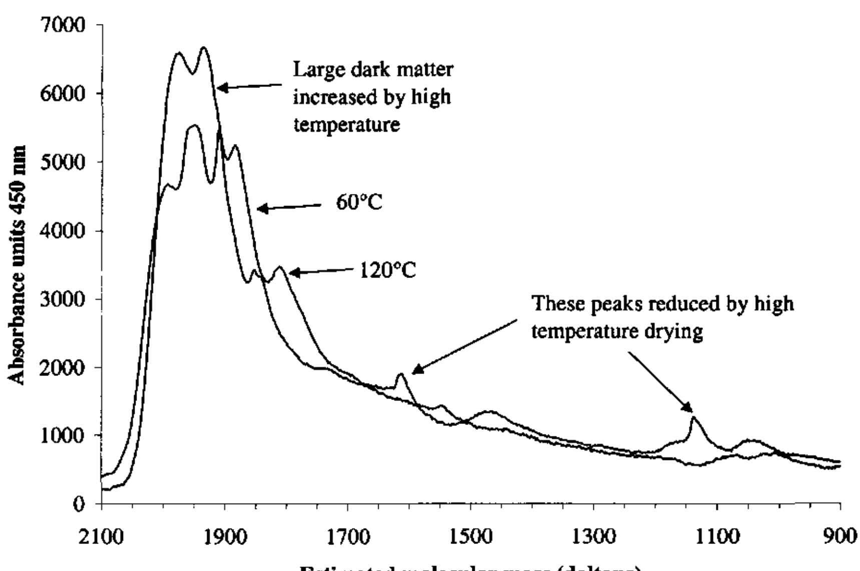

Fig. 4.4 IBMK-insoluble thearubigin-rich fraction from black teas dried at 60°C and 120°C, characterised by SEC-HPLC, monitored at 450 nm. The calibration for apparent mass is based upon the use of neutral condensed tannins (Clifford & Powell 1996; Powell 1995)

Further analysis by size-exclusion HPLC, a technique that separates molecules by molecular size, revealed no systematic differences at 365 nm. At 450 nm increasing drying temperatures appeared to reduce peaks in the 1000-1600 dalton range and increase peaks in the 1900-2000 dalton range (Fig. 4.4).

Findings in Fig. 4.4 are concordant with the observations of Hazarika *et al.*(1984) who observed that when exposed to 100°C, alone, without the presence of TF or EC lower mass thearubigins give rise to higher mass thearubigins.

There was 14% more TF at 140°C (mean drying time 515 s) than at 60°C (mean drying time 2307 s), which is concordant with earlier reports of stewing parallel to over-fermentation at lower temperatures. However, there was no corresponding difference between treatments in residual flavan-3-ols and there was a greater proportion of higher mass TR in the 140°C and 120°C samples (Fig. 4.4). This implies that the TF level is influenced by breakdown during drying rather than fermentation.

Hazarika *et al.* (1984) showed evidence that elevated drying temperature could both retard the development of TR similar to those generated by over fermentation, and promote the transformation of lower mass TR to higher mass TR by thermal change without the presence of flavan-3-ols or theaflavins.

A commercial tea taster assessed the samples (Table 4.2). The comments indicate that the lower temperature is inadequate for generating the blackness required, and that exposure of the dry tea to temperatures of 120 and 140°C generates a burnt taint. Note that a blackish appearance and a bright, coppery infusion are desired.

Table 4.2 Taster's scoring and comments on made teas from thin layer drying.

Temperature	**60°C**	**80°C**	**100°C**	**120°C**	**140°C**
Drying time to 10% mc (s)	2168	1082	705	615	427
Black Tea	Brown	Blackish	Blackish	Blackish	Blackish
Infusion appearance	Bright, Coppery	Fair brightness, coppery	Some brightness, coppery	Some brightness, coppery	Dull
Liquor appearance	Useful	Light Harsh	Full fired Touch harsh	Burnt	Very burnt
Colour	5 ½	6	6	6	5
Strength	5	4	4 ½	3 ½	3 ½
Briskness	5	4	5	4	4
Brightness	6	5	5 ½	4	3
Thickness	4	4 ½	5	4	5
Total score	25 ½	23 ½	26	21 ½	20 ½

From the scores in Table 4.2 it is clear that as some characteristics improve with increasing inlet temperatures, others decline and the most desirable tea is that dried at 100°C. However it must be noted that the differences are minor (especially bearing in mind the relative lack of precision achieved by the taster for the three replicated controls in the tin experiment.), generally only one point on the scoring scale, apart from the brightness of the sample dried at 140°C.

Some of the colour of black tea has been attributed to chlorophyll breakdown products (Mahanta & Hazarika 1985). These were examined by thin-layer chromatography of an acetone extract (Harborne 1982). A clear difference between the teas dried at 140°C and 60°C was observed. Drying at 140°C produced additional grey bands, and of higher intensity, than the teas dried at 60°C. This may correspond with the duller liquor noted by the taster at higher temperature (Table 4.2).

4.4.3 Batch fluid bed dryer

Batch fluid bed drying allowed more tea to be dried in the same experimental trial, but because of the imperfect mixing of the bed, particle treatment will be less uniform. The use of near-infrared moisture metering during the batch fluid bed drying allowed the progress of the experiment to be monitored but with less accuracy than the thin layer method.

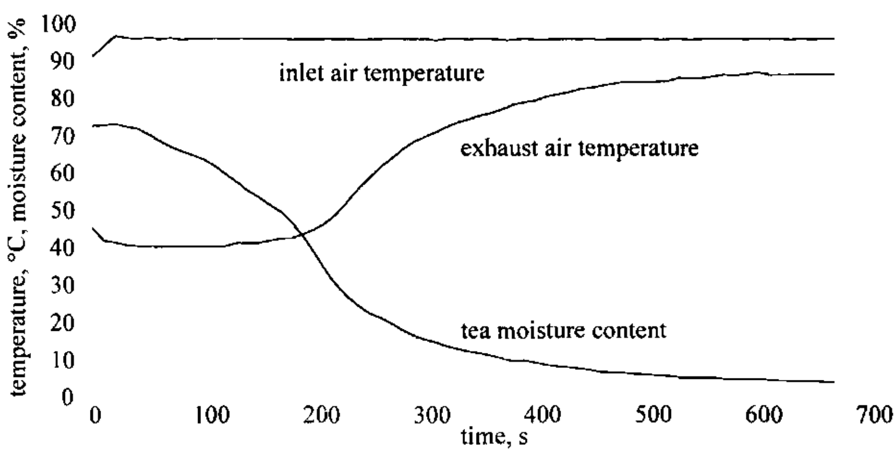

Fig. 4.5 Logged values from batch fluidized bed drying experiment with a fixed inlet temperature of 90°C.

Examples of the data logged during the two groups of experiments are shown in Fig. 4.5 (constant inlet temperature) and Fig. 4.6 (inlet temperature controlled by feedback from exhaust). At the start of drying, the exhaust temperature remains close to 40°C, the saturation temperature of the inlet air, because there is inadequate air to remove all the moisture that is available at the particle surface for evaporation. Tea particle temperature will be very close to exhaust temperature. As drying proceeds and particle moisture content falls, evaporation is limited by internal diffusion, so both exhaust temperature and tea particle temperature rise. This is the normal pattern expected in a drying operation; in a batch dryer the x-axis will be time, in a continuous dryer it will represent distance along the dryer.

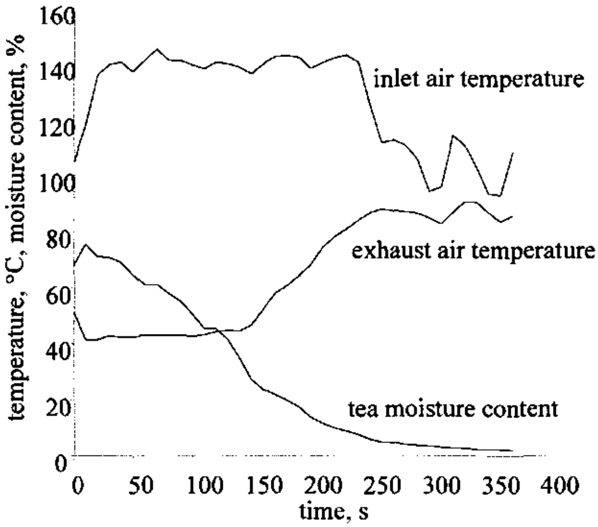

Fig. 4.6 Logged values from batch fluidized bed drying experiment with a maximum inlet temperature of 140°C and a maximum exhaust temperature of 90°C.

It can be seen that, while in Fig. 4.5 the inlet temperature is constant, in Fig. 4.6, once the exhaust temperature reaches 90°C, the inlet temperature is reduced to keep the exhaust below 90°C. This has the effect of speeding up the early stages of drying without overheating the tea in the later stages, simulating a multi-stage continuous dryer. The inlet temperature can be seen to oscillate; this is a consequence of a simple controller being used in a situation where various interactions are occurring.

Drying conditions had a minor effect on theaflavin levels measured by RP-HPLC, but two peaks which were thought to be thearubigins were found to be much lower at 120°C and 140°C, demonstrating that these substances are thermally labile.

Reversed-phase chromatograms of tea liquor show an area of unresolved "hump", thought to represent thearubigins and significantly contributing to a model of quality (McDowell *et al.* 1995). The shape of this hump was not affected by the various drying treatments in the fluidised experiment, yet elevated temperature did increase the magnitude, again supporting thermal polymerisation as demonstrated by Hazarika *et al.* (1984).

Table 4.3 Effects of fluidized bed drying temperatures on drying time, taster's scores and HPLC analysis, averaged over replicates

Max. exhaust temperature, °C	**90**	**90**	**90**	**100**	**100**	**100**	**110**	**Tray**
Inlet temperature °C	**90**	**120**	**140**	**100**	**120**	**140**	**110**	**90-100**
No of replicates	4	2	2	4	2	2	2	2
Drying times								
Time to exhaust air of 60°C, s	288	230	175	260	210	150	240	
Time to 3% mc of tea, s	690	445	370	537	390	325	550	
Taster's scores								
Colour	4	4		4	3 ½	4	4	
Briskness	1	1 ½		1	1 ½	2	1	
Brightness	1	1 ½		1	1 ½	1 ½	1	
Strength	3	3 ½		3	2 ½	3	3 ½	
Colour of infusion	3	3 ½		3	2 ½	3	3	
Colour with milk	3	4		3	2	2 ½	2 ½	
Value	195	208		200	200	210	193	
HPLC values for fermentation products (arbitrary units)								
Theaflavins	232	236	243	229	223	219		233
Unresolved "hump"	693	729	819	759	733	803		721
HPLC values for residual precursors (arbitrary units)								
Gallic acid	90	86	82	88	80	80	79	80
Theogallin	91	93	94	92	93	87	92	88
(+)-gallocatechin	60	57	60	51	58	46	49	94
(+)-catechin	26	67	23	18	26	21	22	45
Caffeine	95	99	97	96	95	91	95	90
(–)-epigallocatechin	84	88	84	84	80	71	76	70
(–)-epicatechin	92	94	86	90	86	85	85	84
(–)-epigallocatechin gallate	76	73	65	75	70	60	62	65
(–)-epicatechin gallate	77	73	68	75	66	59	61	63

With short drying times as used in the fluidized drying experiments, variations in drying had no effect on chemical markers of fermentation and tea quality such as the flavan-3-ols. Other work using the same methods on fermentation rather than drying has shown that these methods are sensitive to changes in tea (Temple & Clifford 1997), and the changes in drying are very much smaller than those in fermenting (Temple 1999).

Table 4.3 also shows that there is very little difference in the levels of the residual flavan-3-ols, and the taster's values show a slight preference for teas made with 90°C and 100°C maximum exhaust temperatures, but with maximum inlet temperatures for 120 and 140°C which produced shorter drying times. The lowest valuations were for the longest drying times, so a time of less than 550 s (approximately 9 min) is to be preferred.

4.4.4 General discussion

Previous work on quality loss in drying has concentrated on the start of the process, while the particle temperature is below about 50°C.

Eden (1976) considered that the acceleration of fermentation reactions in the early stages of drying the most important cause of quality loss. When drying capacity is inadequate early in the process, the activity of leaf enzymes (particularly polyphenol oxidase) is enhanced initially rather than efficiently reduced by thermal denaturation leading to a defect known as 'stewing'. The associated (but ill-defined) chemical transformation leads to undesirable colour and flavour.

Hampton (1996) also discusses the stewing phenomenon in a general overview of quality loss in drying. Johnson and Kanchowa (1984) using the flavognost method for theaflavin analysis (Whitehead & Temple 1992) illustrate the loss of theaflavin in the early stages of drying on a fluid bed dryer with a 20 min residence time. The peak value of 25 μmoles g^{-1} at the end of fermentation fell rapidly to around 20 μmoles g^{-1} in the first ten minutes of drying. In neither of these papers (Hampton 1996; Johnson & Kanchowa 1984) was residence time quantified, and Hampton does not quote the weir height for the continuous fluid bed dryer he is discussing.

It is clear that if the drying rate is high enough at the start of the drying process, stewing will be minimized as the polyphenol oxidases are said to be inactivated once the dhool temperature has risen above 50°C. This implies that the moisture content has dropped so the drying rate also drops. The effect of this is that the exhaust air is no longer saturated and the tea particle temperature will rise, tending towards the air inlet temperature.

The fluid bed dryer used with correct bed loading in these experiments facilitated a rapid rise of exhaust air temperature to above 50°C. Even in the slowest drying fluidized bed experiment (Fig. 4.5) this temperature is reached in less than 4 min, and when the inlet air temperature can reach 140°C it is less than 3 min (Fig. 4.6). Therefore none of the effects of stewing were expected or found.

However, if drying capacity and drying rate are too high a defect known as 'case hardening' occurs because soluble solids are transferred to the leaf surface and exposed to comparatively high temperatures at low water activity. This defect is normally associated with orthodox manufacture where particle sizes may be much larger or with agglomerates of dhool formed by inadequate processing machinery in CTC manufacture. In the present study, no evidence of case hardening was observed, even in the most rapid drying where the endpoint of 3% was achieved in under 5 min.

Drying times in this study were 11 minutes or less, very short compared with times reported by earlier workers (Hazarika *et al.* 1984; Johnson & Kanchowa 1984). The dhool used was estimated to be at its peak TF content when introduced to the dryer, after which it would be expected to plateau before declining, if fermentation is not arrested by drying. In the thin layer experiment variation in TF of up to 14% between extreme treatments was observed (427 s to 2168 s), in the fluidized bed drying (325 s to 690 s) only 6.3%.

There was a decrease in the ratio TF/Hump at elevated temperatures, despite the corresponding inverse relationship between inlet temperature and drying time. This suggests an increase in unresolvable thearubigin by a thermal process, compatible with the findings of Hazarika *et al.* (1984). Analysis of EAITR which approximates to hump by SEC-HPLC shows a change in composition towards higher mass, darker coloured material at higher temperature. A decline in the gallated flavan-3-ols with increased drying temperature could be attributable to thermally driven rearrangement or their incorporation into thearubigins.

Barbora (1962) discusses the maximum temperature during drying, in relation to conventional endless chain pressure rather than fluid bed dryers, and considers lower temperatures favour liquoring qualities. He concludes that higher temperatures may help to preserve flavour, presumably through increasing speed of drying. Hara (1989) found that higher temperatures were required to promote the desirable nitrogenous compounds, formed during drying, in green tea.

Hazarika *et al.*(1984) comment that the products of drying may be influenced by the chemical composition on exposure to temperature. This trial did not include a fermentation time variable. It is possible that alternative TR patterns could be seen if alternative mixtures of precursors were exposed to thermal change. Hazarika *et al.* (1984) proposed that drying could be used to manipulate the flavour of tea and, while considering rolled (large particle) tea, recognised the impact of particle size on the drying process.

The possible contribution of products of Maillard reactions during drying to the blackness and aroma of the dry tea are acknowledged but were not measured. The positive impact of drying on the volatile components of tea has been demonstrated (Ravichandran & Parthiban 1998), the Volatile Flavour Index increasing on drying but the techniques were not available for the present study.

4.5 Conclusion

Previous work has established that rapid drying in the initial stages is vital to prevent loss of theaflavins. The achievement of high drying rates and short drying times can halt the fermentation process quickly. Mean dryer residence times found in commercial practice of 20 min to 1 hour can be reduced to below 15 min for improved quality so this aspect of quality loss should no longer pose a problem.

This study has concentrated on the possible deleterious effects of exposure to elevated temperatures (above 90°C), and the requirement for a minimum temperature to achieve a dry tea sample with the necessary blackness and fired flavour required by the market.

Tea temperatures above 110°C can be considered to always reduce quality. Below this value, the temperature which the dhool reaches is not important as long as the exposure time is short (less than 9 min). When the dhool has high moisture, the exhaust air will be close to the wet bulb temperature of the air rather than the dry bulb temperature. The tea will also be at the wet bulb temperature of the air (normally in the region of 40°C), so much higher inlet air temperatures can be used in the initial drying stage without significant change of quality.

Exposure to a temperature of at least 80°C for a portion of the drying process is required to give a black appearance to the dry tea.

If dryer residence times are below 9 min, it is much more difficult to damage the tea through either over-fermenting or exposure to high temperatures. This is no reason to use excessive temperatures, but values of 140°C at the start of drying falling to 95-100°C at the end will give rapid drying without risk of damage. For dryers with longer residence times such as the ECP (Endless Chain Pressure) type, lower temperatures are required but this will be at the expense of rapid initial drying, particularly with the ECP which is a counter-flow type of dryer where the hottest air meets the driest tea.

4.6 Acknowledgements

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5 Thin Layer Drying of Black Tea*

5.1 Abstract

This paper describes the experiments used to determine the kinetics of tea drying. New thin layer drying apparatus was designed and built to measure the very high rates of drying found at the start of drying, and the results show that the Lewis equation satisfies. The drying rate constant proved to be a linear function of temperature and air flow rate, indicating that tea drying is not only diffusion limited but also a function of convection. The results were validated on independent experiments.

5.2 Introduction

In the manufacture of black tea (Fig. 5.1), the withered tea shoot is macerated, then enzymic oxidation reactions are allowed to proceed before drying from 72% to 3% m.c.w.b. The Orthodox method (Eden 1976) of tea processing uses a cell disruption step which is based upon rolling and produces large leaf fragments. In contrast to this orthodox tea processing method the black tea maceration disrupts the cell structure by the more destructive Cut, Tear and Curl (CTC) machine or the Lawrie Tea Processor (LTP). These processes are commonly used in manufacture for tea bags.

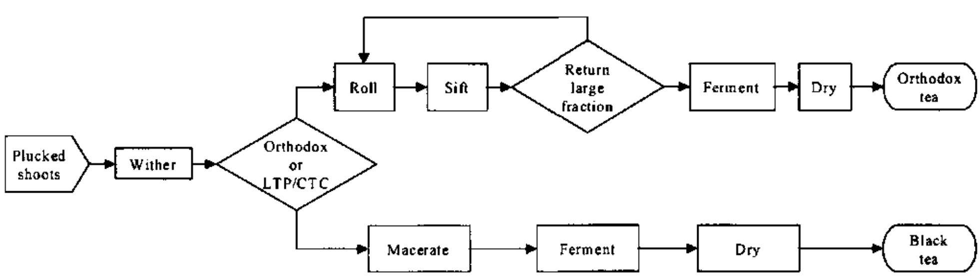

Fig. 5.1. Flowchart of black tea manufacture

Macerated wet leaf is known as "dhool". The elevated product temperatures during drying stop the fermentation of the "dhool". Furthermore during drying the tea moisture is reduced to low levels in order to obtain a transportable product which is not subject to deterioration. In tea processing drying is the major energy consumer, and may have adverse effects on quality. In order to design and control the drying

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stage in an accurate way drying rates for black tea have to be established. There is no published information available for black tea, so the drying kinetics should be determined by experiments.

Drying equations are normally based on models of diffusion. Sophisticated models take into account different rates of diffusion within the particle; this should be more important with the larger particles with intact cell structure such as tobacco leaf (Walton and Casada 1986), grains (Bruce, 1985 on barley, Courtois *et al,* 1994 on maize), and particularly those with a waxy seed coat such as lentils (Tang and Sokhansanj, 1994). Even in green (non-macerated) tea manufacture, Yoshitomi (1988) finds a "two tanks" model appropriate with a leaf length of 40 mm. As tea particle size (mean size of CTC teas is around 0.75 mm and LTP teas 0.5 mm) is much smaller than most grains it is expected that a simper model of internal transport might be appropriate. Selvendran and King (1976) report that for orthodox tea, which is rolled rather than macerated, the membranes and organelles are ruptured but cell wall cleavage only occurs in restricted areas. In macerated teas, however, Harris and Ellis (1981) show that Rotorvane-CTC and to a greater extent LTP a large number of cells are ruptured, cell sap has been mixed and there is good accessibility for gas exchange within the particles of leaf. Water transport is enhanced and reduces the role of diffusion within the particle relative to the surface and air boundary layer resistance. These observations support the use of a simple internal model.

A commonly used simple model, assuming the resistance for water transport is all at the surface of the particle, is represented by an equation analogous to Newton's law of cooling (Parry 1985), also termed the Lewis equation (Jayas *et al* 1991).

$$\frac{dM}{dt} = -k(M - M_e) \tag{5.1}$$

where M is moisture content d.b., M_e is the equilibrium moisture content, t is time and k is a rate coefficient.

The integrated form of this equation is termed the exponential drying model.

$$\frac{M - M_e}{M_o - M_e} = e^{-kt} \tag{5.2}$$

The drying rate coefficient k is not a constant, but will depend on factors such as temperature. Increasing temperature enhances the transport of water in material and improves the mass transfer at particle surfaces. Therefore, it is widely accepted that the drying rate constant k varies with temperature.

In a review of thin layer drying, Jayas *et al* (1991) conclude that air velocity has little effect on drying grains, although in the paper which initiated much of the studies on airflow, Henderson and Pabis (1962) state that it has no significant effects after the first two h. As tea dries in substantially less than an hour, airflow might be of importance. Bruce and Sykes (1983) report that for hops, unlike grain, the drying rate is affected by airflow rate in the range 0.1 to 0.25 m/s. Airflow in beds of grain is turbulent at speeds over 0.08 m/s. The inflorescence of the hop is made up of thin, leaf-like layers where internal resistance to moisture movement is small, so is likely to behave more like tea than grain does. Diamante and Munro (1993) report that over the range 0.5 to 3.0 m/s with sliced sweet potatoes the external mass transfer resistance is significant, as drying rate is affected by airflow. These results indicate that the drying of products is not exclusively governed by diffusion or convection but a combination of these two phenomena and also that the role of the air flow rate cannot be neglected.

Drying studies have been carried out on many crops of agricultural importance, but no data from macerated teas have been found. The only published studies are on green, whole leaf teas by Yoshitomi (1989) which used natural rather than forced convection drying. However no constant rate period was reported, and a single falling rate was valid for the thin layer studies. Macerated tea (dhool) also dries faster than most agricultural produce, from a moisture content of 70% w.b. to 3% w.b. in 20 minutes on an endless chain plate (ECP) type dryer, or less in a fluidized bed dryer.

In this study, the drying rate kinetics are established for black tea. The study includes the dependency of the drying rate on temperature and velocity of drying air. The results are quantified in a relationship useful for mathematical modelling of the process.

5.3 Materials and method

Many designs of equipment have been published in the literature for carrying out thin layer drying experiments, for example Woods and Favier (1993), or Bruce and Sykes (1983). Almost all designs contain the sample within a sealed system with controlled vents, and have provision for interrupting the airflow during weight measurement, to obtain a stable reading.

With the high rate of drying of macerated tea dhool, an interruption in airflow for even 10 s will seriously disrupt the drying, especially at the beginning of the process. Also, the start of an experiment must be carried out rapidly, so that the initial drying air temperature and flow rate are not significantly different to the set values for the experimental run. The initial sample weight must be determined as quickly as possible, before any changes have taken place.

It was decided to use a simpler apparatus for tea (Fig. 5.2), to sacrifice the ability to determine the exhaust air quality, and to lose some resolution on the weight readings, but to enable more rapid loading of the dryer bed and to obtain readings sooner after loading. Instead of the usual arrangement of a drying bed suspended in a closed container, a bedplate and plenum assembly was designed, connected to an air supply by a balanced liquid seal system. The whole bedplate and plenum assembly was suspended from a digital balance. The liquid seal allows the suspended assembly to be independent of the fixed part of the test rig for accurate balance readings. If only a single liquid seal were to be used, there would be a force on the balance due to air pressure; while the balanced seal system does not totally eliminate this effect it is greatly reduced. Because materials for constructing the liquid seal to handle the hottest air to be used were not available, the electrical heating elements were also incorporated in the suspended plenum chamber. Care was taken to avoid the electrical wiring causing spurious readings on the balance. Air was taken from the ambient room condition, pressurised by a centrifugal fan and supplied to the liquid seal apparatus through approximately 3 m of 110 mm nominal bore pvc pipe, into which the airflow measuring sensor was placed.

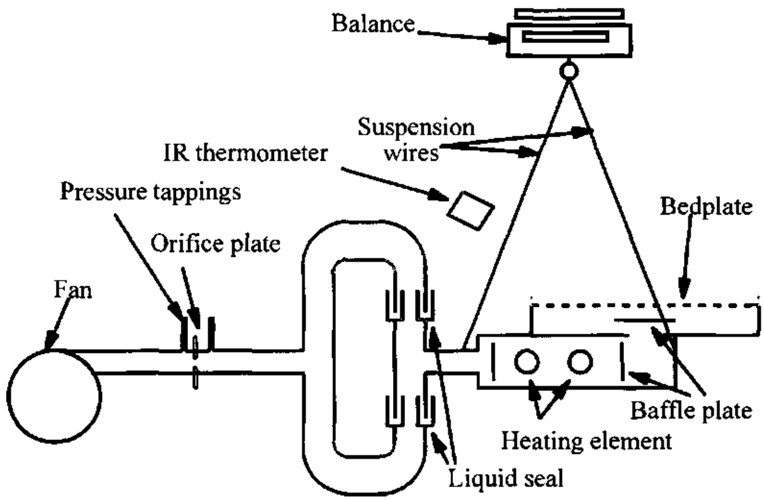

Fig. 5.2. Schematic diagram of thin layer drying apparatus (not to scale)

Some researchers have used downdraft airflow (Bruce and Sykes 1983, Tang and Sokhansanj 1994) which would have allowed working at air velocities greater than the minimum fluidizing velocity without loss of material by elution; however this would also have made the loading of the sample very much slower. In selecting the airflow range to be used on the test rig, the maximum value in terms of metres/second was limited by the risk of elution to less than that used in a fluid bed dryer. However, because of the use of a very much thinner layer than normal in a fluid bed dryer, the mass ratio of air to dhool ranged from below that normal in a fluid bed dryer to well above. For use on a fluid bed dryer, the results will have to be extrapolated to fluidizing velocity and some empirical correction factor may have to be introduced.

To measure the airflow, an orifice plate meter and pressure sensor were used for data logging, in combination with the vane flow meter of a portable airflow instrument. Unlike other authors, no attempt was made to modify the humidity of the ambient air before heating. Instead, the ambient temperature and relative humidity were recorded for each run. This was justified by the fact that even at extremes of ambient conditions of humidity, with drying temperatures above 80°C there is little effect on relative humidity of the drying air. For example, with air starting at an ambient dry bulb temperature of 20°C and at 99% r.h., the relative humidity falls to 4% at 90°C and below 2% at 120°C. McKenzie and Bahu (1991) found that drying rate of different materials is independent of inlet air humidity above 100°C. Therefore any small changes in ambient conditions which may occur during the few minutes duration of a drying run will have a negligible effect on drying rate.

Temperature control of the drying air was by two bar-fire electric elements mounted in the plenum chamber suspended on the balance. These were controlled by a commercial Proportional-Integral-Derivative (PID) controller, sensing temperature by a type K thermocouple fitted just below the drying bed.

Wiring to the elements and sensors was led out of the plenum chamber to the fixed part of the test rig horizontally, to avoid influencing the balance readings. Two independent type K thermocouples measured the below bed temperature, and two more the above bed temperature. These latter did not yield reliable results: because mounting more than a few millimetres above the bed they were influenced by ambient drafts, and mounting them very close to the bed disturbs the spread of dhool on the bed and allow hot air through directly. As an alternative, infrared thermometers were mounted to look at the dhool, but again could be influenced by seeing bare hot bedplate between the dhool particles particularly later in the experimental run after particle shrinkage. The values of exhaust air temperature and dhool temperature were recorded, and sometimes fitted the model well but are unreliable on other occasions. Analogue sensor values were converted on a data logger unit, and samples at 1 s intervals were logged on a computer. The balance was also set to send values to the computer at 1 s intervals. Because these two sets of readings came from separate measuring systems and were not synchronised, the values were averaged over a 20 s period and saved in the disk at these intervals.

The procedure for an experimental run was first carried out in a dummy bedplate (the same weight as the operating bedplate) on the test rig, with no dhool. The instruments were turned on and the balance tared; the suspended portion of the liquid seal was checked for free movement. The fan output was set to give the desired airflow and a suitably sized orifice plate fitted to the air duct. The required temperature was set on the PID controller. Six equal portions of dhool were weighed out, and a sample of dhool was analysed for moisture on an infrared moisture balance. The six equal portions of dhool were loaded onto the six marked areas on the bedplate. (This procedure was adopted to ensure an even spread of dhool). Once the temperature had stabilised and the airflow was at the set value, the balance was checked for drift. It was re-tared if necessary before removing the dummy bedplate and replacing with the loaded bedplate, as quickly as possible and without disturbing the liquid seal.

The data logging was turned on as soon as the bedplate is located. The initial balance reading was noted together with the ambient temperature and humidity, the airflow reading and the dhool moisture.

The end of the run was determined when the change in balance reading was less than 0.1 g in 30 s, the data logging turned off, the bedplate removed and replaced with the dummy. The balance tare reading was then checked for drift. The dry tea weight and moisture content could be determined as a further check on system operation. The data logging system was re-initialised for the next run.

The series of experiments was designed to cover as broad a spread of conditions as possible. Inlet temperatures spanned 50°C–150°C by 10°C steps. Superficial air velocity was varied from 0.048 by 0.01 m/s steps to 0.14 m/s, then by 0.02 m/s steps to 0.63 m/s. Four rates of plate loading from 0.87 to 2.6 kg/m^2 were used. Four varieties of tea with differing characteristics were used (*Camellia sinensis* clone SFS150, clone SFS204, seedling tea and a mixture of clones) and maceration was by CTC or LTP. At the highest airflow rates, the higher temperatures could not be achieved due to the heater power available. Starting moisture contents varied naturally with weather conditions and withering time, and were difficult to control accurately, particularly with small samples. It was not possible to carry out a complete factorial experimental design. All sample types were tested using at least two temperatures including 100°C and a range of airflow rates.

Perfect replication of the experimental runs was not possible, as drying proceeded one sample at a time. Withered tea samples and fermenting dhool change with time so the subsequent sample would have had a longer time at one or other stage of the process. Instead, enough samples were dried to give overlapping data sets. The data were loaded into a spreadsheet for calculation of the rate factor for every 20 s of every experimental run. Regression analysis was used to determine which of the variables contributed to the variation in rate factor.

The reproducibility of the experimental runs will be indicated by the spread of values for the rate factor k, and by validation on new samples of the rate factor after determination on the original data sets.

The errors anticipated in the work concerned practical techniques which could swamp any theoretical considerations such as those analysed by Woods and Favier (1993). The problems in achieving an even spread of dhool, which is slightly sticky, and of measuring the start of the drying process at high inlet temperatures and airflow rates were the most difficult to overcome. To determine whether the results were influenced by the amount spread on the bedplate, experimental runs were carried out with varying loads. Particle shrinkage reduced the bed plate coverage during an experimental run.

The major measurement error was in the weighing. Because of the tare weight of the plenum chamber and heater system, the electronic balance was restricted to 0.1g resolution. For the first half of each experimental run, when the sample weight was high, and the rate of drying also high, this resolution did not cause problems. However, as the run proceeded, and the rate of weight loss dropped to less than 0.1 g per sampling interval, this was the major cause of errors.

5.4 Results

A total of 172 experimental runs were carried out. Occasional runs were discarded because of excessive noise; the cause of this was disturbance to the apparatus during loading which displaced the suspended part of the test rig from its normal position. This could have been avoided by the use of air bearings, as in Bruce and Sykes (1983), but because runs took a short time only it was decided to keep the apparatus as simple as possible and discard any data that were unacceptably noisy.

Several methods of data analysis were tested; the most logical approach for estimating the k-value is to fit the Lewis equation directly to the data. However the large number of points in the low moisture range biases the result towards the least accurate measurements. The most accurate information on k is in the first part of the curve. To utilise as much data as possible with greatest accuracy other approaches should be used. One of these methods is to give more weight to the points in the beginning of the data, and less towards the end. Another method was used with these data. For each run, a graph was plotted of the weight of sample against time, and the value of k determined at each sampling interval. This method took account of small variations in experimental conditions through the run, and provided the greatest degrees of freedom for statistical analysis. It was the method finally used.

The rate factor k was determined for each sampling interval by the following formula, derived from Equation 5.2:

$$k = \frac{\ln(M_1 - M_e) - \ln(M_2 - M_e)}{t} \qquad (5.3)$$

where M_1 and M_2 are the start of sample period and end of sample period moisture contents respectively, M_e is the moisture content at equilibrium with the inlet air, and t is the sample time interval. For a constant dry matter, weights are equivalent to dry basis moisture content. For air temperatures over 100°C (the majority of experiments) the equilibrium moisture content is defined as zero (Temple and van Boxtel) and for all other inlet air conditions used in the experiments the equilibrium moisture was small; therefore the value for M_e could be set to zero. Analysing the effect of this assumption showed that the worst case error which could occur was in the three runs carried out at an inlet air temperature of 50°C. Here the error in the calculated value of k was still less than 1% over the first 6 min of the run, less than 2% over the next 6 min and only rose above 3% for the last min of the experiment. Therefore this term could be omitted to simplify the calculations.

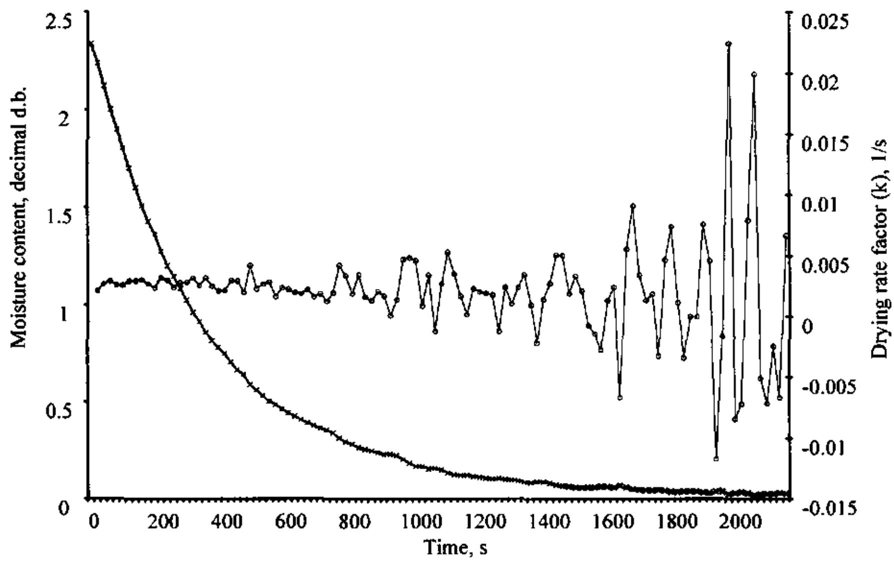

Fig. 5.3. Weight loss and rate factor during an experimental run. Thin layer run 206 100°C 0.18 m/s 70.1% m.c. w.b; × *Moisture content, decimal d.b.; o Rate factor k calculated at each sampling interval*

As shown in Fig. 5.3, the rate is very steady at the start of a run, but when the weight loss in each sampling interval approaches the resolution of the balance, some uncertainty is introduced which causes some large fluctuations, although still about the same mean value. The least "noisy" parts of all runs were selected, taking all values up to the point where the noise became 10% of the mean value.

As theory suggested that temperature would be a major component of *k*, the amount of the variation in *k* caused by temperature was determined by regression analysis. A plot of the results is shown in Fig. 5.4. The regression value R^2 of 0.21 indicates that only a small part of the variation can be explained by temperature.

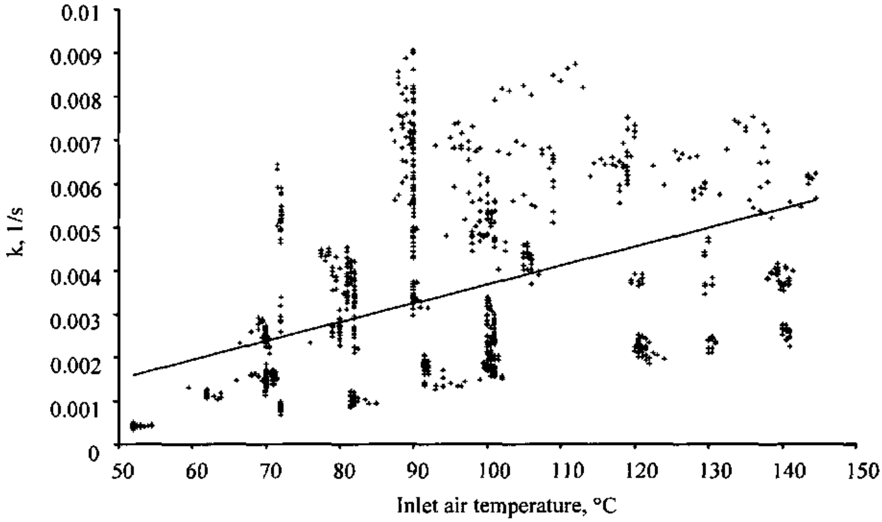

Fig. 5.4. Variation of rate factor *k* with inlet air temperature

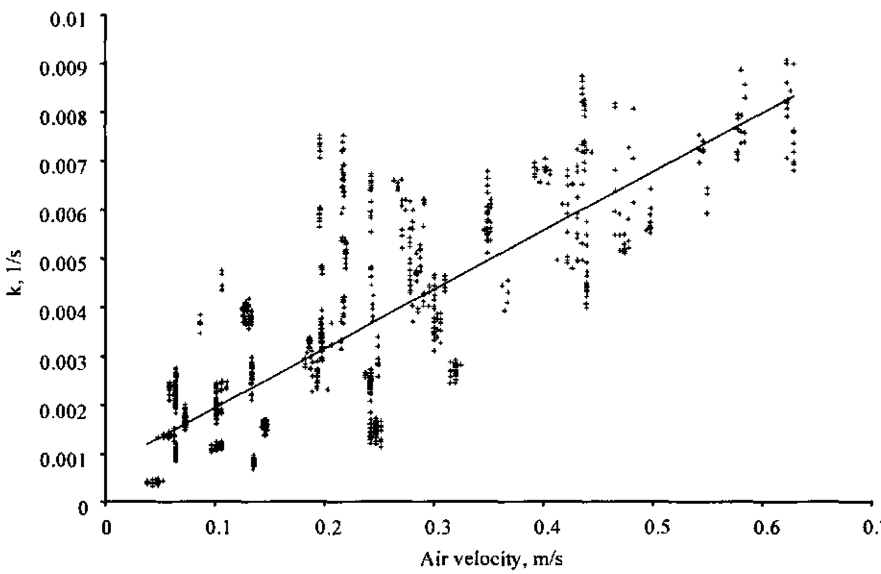

Fig. 5.5. Variation of rate factor *k* with superficial air velocity

The independent variables were tested in the same way, but the only one to explain any of the variation was the superficial air velocity. Figure 5.5 shows how the values for *k* vary with air velocity, giving a regression value R^2 of 0.64. This indicates that air velocity is a major factor.

There was no discernible difference between the tea varieties, the method of maceration, bed loading rate or the start moisture content. There was no difference due to fermenting times once half the normal fermenting time had passed. Totally unfermented dhool dried at a different rate to dhool fermented for 50% or more of the normal time, but unfermented dhool is never dried in the manufacture of black tea.

Regression of the product of air velocity and temperature in the following form:

$$k = (0.00028 \times (T - 45) \times u) - 0.00067 \quad (5.4)$$

where T is temperature in °C and u is superficial air velocity in m/s gave the best result. The R^2 value was 0.93 and the results are shown in Fig. 5.6; the remaining variation was due to random jitter. Improved apparatus should reduce the spread of values and improve the value of R^2.

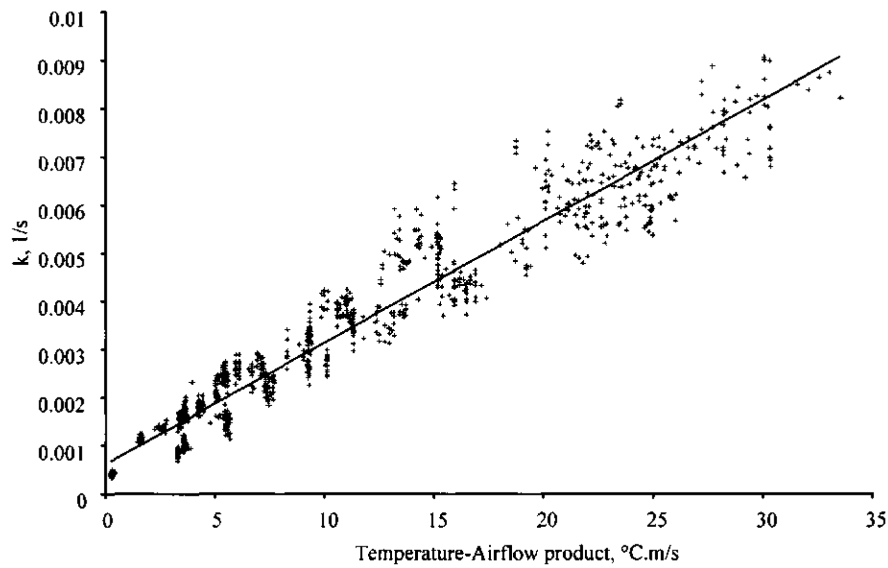

Fig. 5.6. Variation of rate factor *k* with temperature-airflow product

Thin layer drying experiments, totally independent of the runs used to determine the value of k, were performed to validate this result, three results from which are shown in Fig. 5.7

The predicted results started with the mass and moisture content of dhool as used in practice, and employed the value of k determined above in the diffusion drying equation. Other runs (10 in total) spanned a temperature range from 70 to 150°C, and airflows of 0.06 m/s, 0.42 m/s and 0.62 m/s. These experiments showed comparable results.

5.5 Discussion

In the independent validation experiments, the good fit of the values predicted by the Lewis model to the actual measurements confirms the validity of the model for the drying of black tea.

These results show a very much stronger dependence on airflow than the results on other agricultural products reported in the literature. There are three main factors which might account for this airflow dependence. The first is the size of particle which is very much smaller than for other agricultural produce. The second is the almost complete breakdown of the cellular structure of the particle, reducing the internal resistance to diffusion to a very small value. These two lead to a greater rate of moisture loss than other crops described in Table 5.1, averaging over 4 kg/m^2h, at least ten times greater than the other experiments cited.

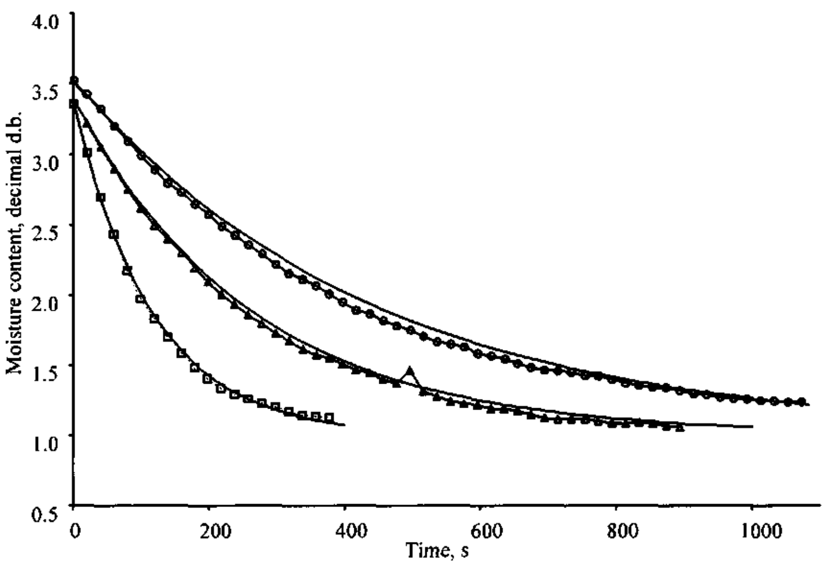

Fig. 5.7. Actual and predicted results from thin layer validation experiment; —Δ— *test at 80°C, 0.32 m/s and 70.4% m.c.(w.b.); —□— test at 90°C, 0.62 m/s and 70.2% m.c.(w.b.); —o— test at 90°C, 0.62 m/s and 71.6% m.c.; ———, predicted*

The third is the very high concentration of solutes in the cell sap; most agricultural materials being dried have a high proportion of less highly osmotic substances such as starch, as they are storage organs. Tea leaves are actively synthesising parts of the plant, and have 30% of the dry weight as phenolics, 3 to 4 % as caffeine, 4% as amino acids and 4% as soluble carbohydrates, totalling 42% of dry weight readily soluble in cold water. Starch forms only 4%, other polysaccharides 12% and protein 15%, which with 5% inorganics makes up 36% partially soluble in hot water. The remaining fraction is made up of cellulose, lignin and lipids which are insoluble in water (Robertson 1992).

Table 5.1 Comparison of thin layer tea drying with other crops.

Material	Tea†	Barley‡	Rapeseed§	alfalfa**	Sweet potato††	Lentils‡‡ (est. area)
Area of thin layer bed, m^2	0.058	0.135	0.135	1	0.032	0.05
Sample weight, kg	0.09	0.35	0.55	1.5	0.4	0.1
Starting m.c. decimal d.b.	3	0.25	0.26	6	2.2	0.245
End m.c. decimal d.b.	0.03	0.05	0.06	0.05	0.1	0.06
Duration of run, h	0.25	130	2	5	120	24
Air velocity, m/s	0.3	0.5	0.17	0.3	3	0.3
Average evaporation, whole operation, $kg/m^2.h$	4.69	0.0040	0.42	0.26	0.071	0.016
Water lost average, drying operation, kg/h	0.27	0.00054	0.056	0.257	0.0023	0.00082
Air flow, m^3/h	62.208	243	82.62	1080	349.65	54
Water evaporated : air ratio, kg/m^3	0.0043	2.21×10^{-6}	0.00069	0.00024	6.55×10^{-6}	1.51×10^{-5}
Air inlet temperature °C	100	30	60	60	70	40
Diameter of sphere representing particle d, m	0.0005	0.004	0.002	0.0024	10	0.004
Density of particle, kg/m^3	1.1	1.1	1	1	1	1.1
Superficial air velocity, m/s	0.3	0.5	0.17	0.3	3	0.3
Viscosity of air $\mu \times 10^7$, $N.s/m^2$	220	184	200	200	200	180
Reynolds number (sphere) R_e	7.5	119.6	17	36	1500000	73
Diffusivity of water vapour in air, D_v, m^2/s	2.74×10^{-5}	2.74×10^{-5}	2.74×10^{-5}	2.74×10^{-5}	2.74×10^{-5}	2.74×10^{-5}
Schmitt number S_c	0.73	0.61	0.73	0.73	0.73	0.60
$a = \dfrac{0.66 S_c^{1.7}}{(1+0.59 S_c^{0.5})^{0.33}}$	0.337	0.25	0.34	0.34	0.34	0.24
Sherwood number Fixed bed $S_h = 2 + \dfrac{a R_e^{1.7}}{1 + S_c^{1.2} R_e^{1.2}}$	3.20	6.94	3.93	4.89	604	5.81
Mass transfer $m = \dfrac{S_h \mathcal{D}_v}{d}$	0.175	0.048	0.054	0.056	0.00167	0.040
Estimated diffusivity, water in dry matter, D_w m^2/s	2.78×10^{-11}	1.00×10^{-11}	1.00×10^{-11}	1.00×10^{-11}	1.00×10^{-11}	1.00×10^{-11}
Biot number $= \dfrac{m.d}{\mathcal{D}_w}$	3.15×10^{6}	1.90×10^{7}	1.08×10^{7}	1.34×10^{7}	1.66×10^{9}	1.59×10^{7}

† This study

‡ Sun & Woods (1994)

§ Crisp & Woods (1994)

** Patil et al (1992)

†† Diamante & Munro (1993)

‡‡ Tang & Sokansanj (1994)

A combination of the breakdown of the cell wall structure and the high proportion of solutes will mean that evaporation will occur from a liquid surface of increasing concentration of solutes. The falling rate effect in this case may be due to evaporation from a free surface of a liquid with increasing osmotic pressure. This would give a similar effect to moisture transfer from a droplet, which also obeys Fick's diffusion law (Furuta 1992). Using data from published studies on other crops, a comparison of some important parameters was made with tea. In addition to the sources cited above, data were also taken from Sun and Woods (1994), Crisp and Woods (1994), and Patil *et al* (1992). Some of the data required were not available in the publications; typical values for the appropriate crop were used.

In Table 5.1 the value for diffusivity of water in dry matter is taken from Yoshitomi (1988). This shows that for tea, the amount of water evaporated per unit volume of air is much greater than for other thin layer drying experiments. The Biot number is an important indicator to determine whether the resistance for water transport is a matter of diffusion or convection. For low numbers (<5000) convection is dominating, for high numbers (>50000) diffusion dominates the transport of water. The estimated Biot number for tea is significantly lower (3.15×10^6) than that of other agricultural products (lowest in Table 5.1 is lentil at 1.59×10^7) which indicates that convection plays a more important role for tea drying although diffusion is still important. However it must be noted that the value of diffusivity of water in dry matter was estimated in the calculation of the Biot number from Yoshitomi's value for rolled leaf rather than macerated particles of leaf. It is likely that the actual value for macerated tea will be much lower than that estimated.

5.6 Conclusions

Results from over 170 thin layer drying experiments were used to derive a drying rate factor for the Lewis drying equation. The value for the rate factor was confirmed by independent experiment.

The drying rate factor k for macerated tea particles was found to be dependent on air temperature as expected, and was observed to be strongly dependant on air flow velocity, in contrast to the results from other research. The reason why tea dries in a different way to most other agricultural produce may be because of the small particle size, the breakdown in cellular structure and the high concentration of soluble substances in the free cell sap.

A single function describes the whole process of thin layer drying of tea from 70% m.c. w.b. down to 3%. The drying rate is directly proportional to the superficial airflow and the air temperature. The absence of a constant rate period is in accordance with the published results.

To capture the drying rate at the start of the experiment more accurately and ensure that any constant rate period was detected, the design of test rig sacrificed accuracy at the end of the experiment when rates were low.

5.7 Acknowledgements

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6 Modelling of Fluidized Bed Drying of Black Tea*

6.1 Abstract

A mathematical model was developed for fluidized bed drying of tea. This was developed into a simulation model which can be used for either batch or continuous drying. The simulation model was validated on a thin layer drying test rig, and on fluidized bed dryers. To account for the loss of efficiency between thin layer and fluidized bed, an efficiency factor of 0.6 was used, which was appropriate for, and validated on, an experimental batch dryer, a pilot scale continuous dryer and a commercial dryer in a tea factory. The simulation model is useful for design, operational setting and control system design. The constant rate drying phase is shown to be a property of the drying air rather than the material being dried.

6.2 Notation

a	air mass flow, kg/s	W	water, mass, kg
A	air mass, kg	X	moisture content, decimal d.b.
c	constant		(kg water/kg dry matter)
C_p	specific heat, kJ/kg.°K	z_b	bed area, m^2
h	enthalpy flow, kJ/s	ρ	density, kg/m^3
H	total enthalpy, kJ		
ΔH_v	latent heat of evaporation, kJ/kg	Subscripts	
J	evaporation rate, kg H_2O/kg dm s	a	air
k	drying rate constant, s^{-1}	b	bed
L	bed depth, m	d	dhool
m	flow rate of dry matter, kg/s	e	equilibrium
M	dry matter mass, kg	h	weir
T	temperature, °C	i	in
t	time, s	m	dry matter
u	superficial air velocity, m/s	o	output
w	water, mass flow rate, kg/s	w	water

* Published as Temple, SJ; van Boxtel AJB (1999) Modelling of fluidized bed drying of black tea. Journal of Agricultural Engineering Research 74(2) 203-212

6.3 Introduction

Black tea is manufactured from shoots of the tea bush which have been withered, macerated and undergone enzymic oxidation, then dried. The drying operation reduced the moisture content from around 71% to 3% w.b., with varying time between 10 and 60 min. Fluid bed drying is the normal method for drying black macerated teas. A continuous dryer is used (Fig. 6.1), the macerated and fermented tea (dhool) being fed in at one end of a rectangular bed, and the dry, made tea discharged over a weir at the opposite end.

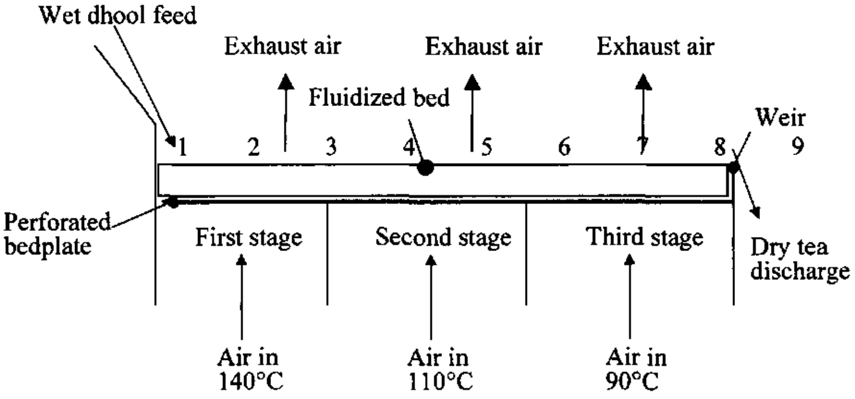

Fig. 6.1. Schematic diagram of three stage fluidized bed dryer. Numbers 1 to 9 represent temperature measurement positions

The dryer can have a single air supply at a constant temperature, or, more commonly, have two or three stages with the inlet air temperature being lower as the tea dries. The first stage of the dryer is often vibrated to aid fluidization of the wet dhool.

Although a fluidized bed dryer is a very simple piece of equipment, being basically a box with a perforated base, an air stream vertically upwards and product flow across the bed, there are many interactions between the factors influencing drying. In particular the product flow decreases in speed as the product dries, thus affecting drying rate.

The objective of this study is to develop a model for use in the design and control of fluidized bed dryers. In industry there are many different configurations so the model should be modular, enabling different configurations to be assembled to model the various types found in practice. A dynamic model is required to study batch drying, start-up conditions, and for the dynamics of the control system. This model requires an understanding of the drying properties of tea. These have been established for macerated black teas as found in Southern Africa in the work of Temple and van Boxtel (1999a) on equilibrium moisture relations, air requirements for fluidization (Temple & van Boxtel 1999b) and drying rate (Temple & van Boxtel 1999c).

Despite the popularity of the fluidized bed dryer for black tea, there are very few published accounts concerning the design and operation of such dryers. Hampton (1992) presented a general overview, while Shah and Goyel (1980), Bedi (1995) and Kirtisinghe (1974) were concerned with the overall features of specific machines. The work by Johnson (1985a, 1985b and 1989) in Malawi cites measurements of commercial dryers in operation, and draws some valuable conclusions but does not approach the fundamentals of dryer operation.

Some extensive modelling work has been carried out in China and Japan on tea drying. Yin Hongfan (1986) and Yoshitomi (1987) have published studies, but the method of manufacture of tea considered is for either orthodox (whole leaf) tea or green tea (whole leaf, unfermented). The conclusions cannot be transferred to the drying of macerated, fermented teas.

6.4 Model of fluidized bed drying

The starting point for modelling is a continuous stirred tank reactor, where the product is well mixed. This model approach is valid for simple fluidized batch systems. The approach can be extended to cover a continuous fluidized bed dryer which approaches plug flow by placing a number of well-mixed systems in series.

The following assumptions are made in the model:

- The fluidized bed exhaust is open to the atmosphere, so the top is at atmospheric pressure.
- The pressure differential across the bed of tea is small, so drying is at constant pressure
- No energy is gained or lost in the dryer, so the drying process is adiabatic.
- For a constant weir height, bed loading is constant while dhool is being fed at a greater rate than evaporation.
- Well mixed flow of dhool from inlet to outlet (Plug flow can be approached by series connection of well mixed systems).
- Plug flow of air from inlet at bottom to exhaust at top.
- Complete mixing of air and dhool particles (No bubbling fluidization).
- Heat exchange between particle and air is complete so that air exhaust temperature equals particle temperature.
- Mass of air resident in the bed is negligible.

In previous work (Temple & van Boxtel 1999c) it was found that the equilibrium moisture plays an important role in the equation for drying rate:

$$\frac{dX}{dt} = -k(X - X_e) = -J \tag{6.1}$$

where X is moisture content, decimal d.b., X_e is equilibrium moisture content, t is time, s, k the rate factor, s^{-1}, and J the evaporation rate, kg H_2O/kg dm s.

Although a thick bed is involved here, traditional thick layer models are not appropriate as they assume the layers do not move during the drying process. In a fluidized bed, the material being dried is well mixed vertically, so that a particle that has been in contact with exhaust air will soon meet incoming air. The thin layer model is not expected to be perfect, but will be more appropriate than a normal thick bed approach.

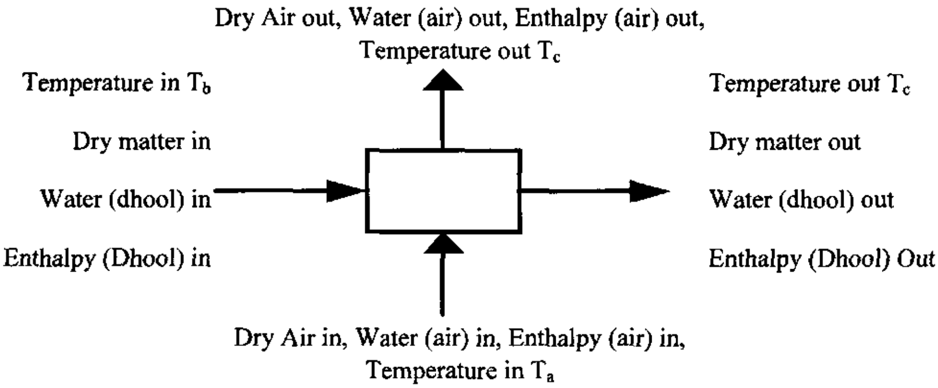

Fig. 6.2. Input/output model

Because of the intended use for dryer control and to describe the transients during batch-wise drying, the model is based on a set of differential equations. The state variables for these differential equations (Fig. 6.2) must be: dry matter mass, water mass, air mass and enthalpy. For input/output modelling, it is more convenient to consider temperature rather than enthalpy, as temperature is a variable that can be measured. If the various masses are known as well as temperature then the enthalpy can be calculated.

6.4.1 Dry matter balance

$$\frac{dM_b}{dt} = m_i - m_o \tag{6.2}$$

where M is mass of dry matter in kg, m is the flow rate of dry matter, kg/s and subscripts b, i and o represents the bed, in and out respectively.

6.4.2 Water balance

Water in dhool:

$$\frac{dW_b}{dt} = w_{d,i} - w_{d,o} - M_b J \tag{6.3}$$

where W is mass of water in kg, w is the mass flow rate of water in kg/s, the subscript d represents dhool.

Water in air:

$$w_{a,i} + M_b J = w_{a,o} \tag{6.4}$$

6.4.3 Air balance

$$\frac{dA}{dt} = a_i - a_o \tag{6.5}$$

where A is mass of air in kg and a is the mass flow rate of air in kg/s.

As the process operates at atmospheric pressure, and the volume of air in the control volume is much greater than the volume of dhool, then:

$$\frac{dA}{dt} = 0 \tag{6.6}$$

6.4.4 Enthalpy balance

The total enthalpy accumulation in the system, i.e. of air and product, is given by

$$H = h_{i,d} + h_{i,a} - h_{o,d} - h_{o,a} \tag{6.7}$$

where H is the total enthalpy accumulation, kJ and h is the enthalpy flow in kJ/s. Each term of h will consist of a component for dry air or dhool and a component for water. Therefore, from the point of view of external flux:

$$\begin{aligned} H &= C_{p,m}(m_i - m_o)(T_o - T_{i,d}) + \\ &C_{p,w}(w_{i,d}T_{i,d} + w_{i,a}T_{i,a} + (w_{o,d} - w_{o,a})T_o) + C_{p,a}(a_i - a_o)(T_o - T_{i,a}) \end{aligned} \tag{6.8}$$

where $C_{p,}$ is specific heat in kJ/kg and T is the temperature in °C. Internal to the bed the total enthalpy accumulation will result in temperature change of the bed and is used for evaporation:

$$\begin{aligned} H &= \frac{d(C_{p,m}M_b + C_{p,w}W_b)T_b}{dt} + \frac{d(C_{p,a}A_a + C_{p,w}W_a)T_a}{dt} + M_b J \Delta H_v \\ &= (C_{p,m}M_b + C_{p,w}W_b)\frac{dT}{dt} + T(C_{p,m}\frac{dM_b}{dt} + C_{p,w}\frac{dW_b}{dt}) + M_b J \Delta H_v \end{aligned} \tag{6.9}$$

where ΔH_v is the latent heat of evaporation of water in kJ/kg, and the subscripts m and w represent dry matter and water, respectively.

If the system is adiabatic, then Eqns (6.7) and (6.9) may be combined. Translating into temperature terms, and assuming $T_{a,o}=T_b=T$ where T is temperature, °C, then:

$$(C_{p,m}M_b + C_{p,w}W_b)\frac{dT}{dt} = C_{p,m}(m_i T_i - m_o T_o) + C_{p,w}(w_{i,d}T_{i,d} + w_{i,a}T_{i,a}$$
$$- T_o(w_{o,d} + w_{o,a})) + C_{p,a}a_i(T_i - T_o) - T(C_{p,m}\frac{dM_b}{dt} + C_{p,w}\frac{dW_b}{dt}) - M_b J \Delta H_v \quad (6.10)$$

6.4.5 Bed load

If bed depth L in m, is equal to weir height L_h and evaporation is less than the dhool feed rate:

$$m_{i,d} + w_{i,d} + w_{i,a} \geq w_{o,a} \quad (6.11)$$

then bed loading will be constant. Therefore under these conditions,

$$\frac{dM_b}{dt} + \frac{dW_b}{dt} = 0 \quad (6.12)$$

and, combining Eqns (6.2) – (6.4) gives

$$m_{i,d} + w_{i,d} + w_{i,a} - m_{o,d} - w_{o,d} - w_{o,a} = \quad (6.13)$$

Using the bed density the total load can be determined

$$M_b + W_{d,b} + A_b + W_{a,b} = \rho_b z_b L_h \quad (6.14)$$

where z is the area in m^2 and ρ is the mean density in kg/m^3.

As the mass of air, and moisture in the air, is very small compared to the mass of dhool, then

$$M_b + W_{d,b} = \rho_b z_b L_h \quad (6.15)$$

If bed depth is less than weir height, $L < L_h$ or evaporation is greater than dhool feed rate,

$$m_{i,d} + w_{i,d} + w_{i,a} < w_{o,a} \quad (6.16)$$

then

$$L = \frac{M_b + W_{d,b}}{z_b \rho_b} \quad (6.17)$$

considering the bed as a whole.

6.4.6 Evaporation rate

Subject to the constraints below, the drying rate of the dhool is

$$J = k(X - X_c) \tag{6.18}$$

where

$$k = c_1 u(T_{a,i} - 45) - c_2 \tag{6.19}$$

T is the temperature in °C of the inlet air stream, u is air velocity in m/s and c_1 and c_2 are constants. (Note: the exhaust air qualities are different to the inlet, and a more sophisticated model would take into consideration the temperature and air moisture content gradient across the bed).

6.4.7 Constraints on evaporation rate

Evaporation rate cannot be more than the evaporative capacity of the air. The energy available to supply the latent heat required is that remaining after raising the dhool to the exhaust temperature of the air.

6.4.8 Other properties used

The psychrometric equations for determination of air properties were taken from ASHRAE (1981) and CIBSE (1975). The value for the specific heat of tea was taken as 0.96 kJ/kg dry matter (Yoshitomi 1987). The value quoted by Hongfan Yin (1985) is somewhat higher at 1.44 kJ/kg dry matter. The model was not found to be sensitive to changes in specific heat of this order of magnitude.

6.4.9 Simulation model

These equations were used to create a simulation model using the Matlab and Simulink packages. The Simulink package is block oriented and offers possibilities for setting up functional libraries. The model consists of several main blocks which are inter-linked. In Fig. 6.3 the functional blocks are given for one simulation section. The calculation of the exhaust temperature, and the water and dry matter determinations are performed using integrators. These have to be seeded with starting values. To model a continuous dryer, starting up from empty, a very small value is used for initial dry matter and water to avoid division by zero. To model a batch dryer, the dhool mass flow input is set to zero and the load is entered as the initial values.

In a continuous dryer, until the bed height reaches the weir height, there is no discharge; when it reaches weir height, any excess is discharged at the average moisture content of the bed. A switch in the calculation block determines if the bed load is at or below the maximum, and another switch using the same trigger determines whether discharge occurs or not.

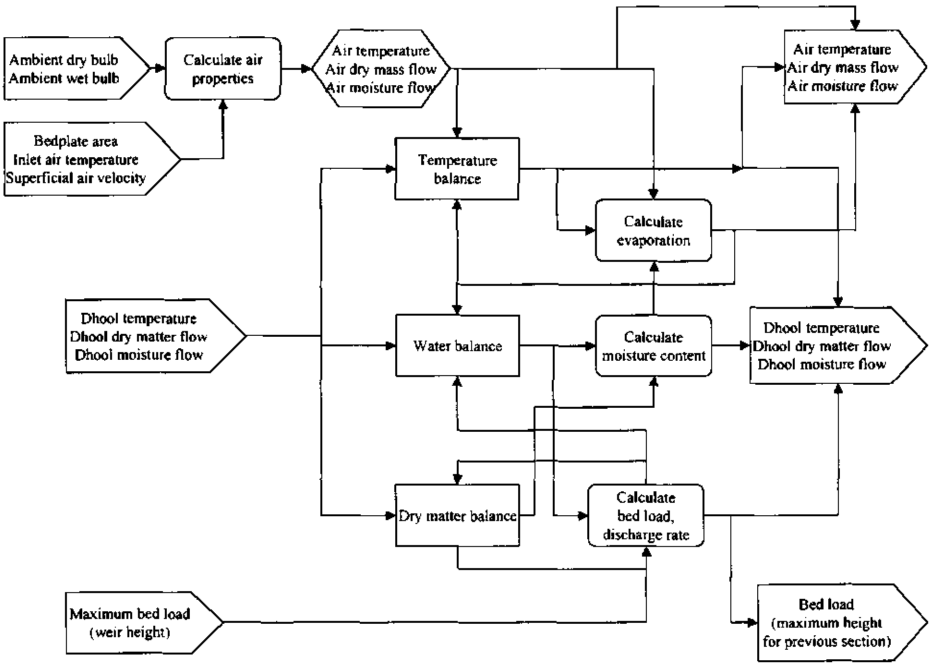

Fig. 6.3. Outline of simulation model

To model each section of a dryer, three units as in Fig. 6.3 are linked together as in Fig. 6.4, with all inlet air conditions being the same. Three of these sections are also linked together, again as in Fig. 6.4, but with different air conditions for each stage. As the model is designed for simulation of both start up and continuous operation, the loading of the bed took required special attention. In industrial dryers, at start up tea spreads evenly over the total bed plate and the bed height increases until the weir height is attained. Start up is simulated with the sequence of subsections where a given section is filled up to a small threshold value above the height in the following section. Before that moment there is no discharge from the section and after that moment all feed less evaporation is fed into the following section. Once the level is equal in all sections, the sequence will continue until the weir height is attained. In this procedure, a virtual weir is used for each stage which corresponds to the height to which the next section has been filled. This actual weir height and bed load in the following section are necessary in the calculations in the current section and therefore in Fig. 6.4 the information flow of the actual bed load and weir height go in the opposite direction of the information flow for tea. Using a small threshold gives a simulation of even filling of the bed. In practice, discharge can be seen to stop very shortly after an interruption to feed to the dryer and this behaviour is modelled correctly.

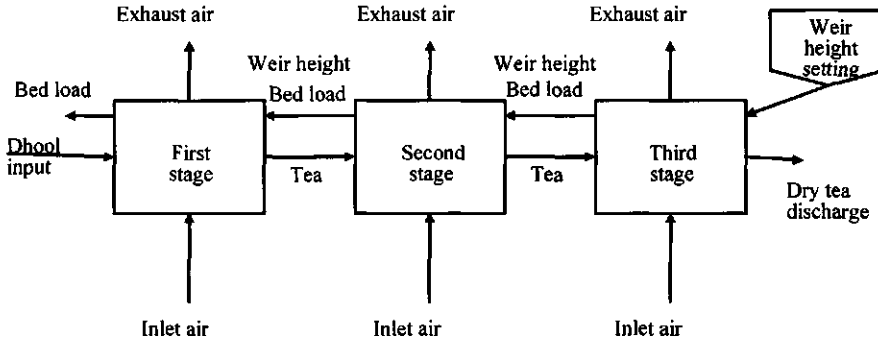

Fig. 6.4. Assembly of modules into a continuous flow model.

If separate weirs are required for each stage, the inter-coupling of bed height for the stages is removed. It is relatively simple to model the recycling of exhaust air from one section to the next, or any other configuration that might be found in practice.

6.5 Additional information

Some additional data were required to determine the relationship between bed loading and weir height, and to check the assumption of equilibrium between air and dhool. Measurements were taken on the pilot-scale lines continuous fluidized-bed dryer at Tea Research Foundation, Malawi.

Figure 6.5 shows that the air does not fall in temperature once it is about 10 mm above the bedplate, with a weir height of 25 mm. Therefore with a weir height of more than 10 mm, the assumption of equilibrium between exhaust air and product is justified.

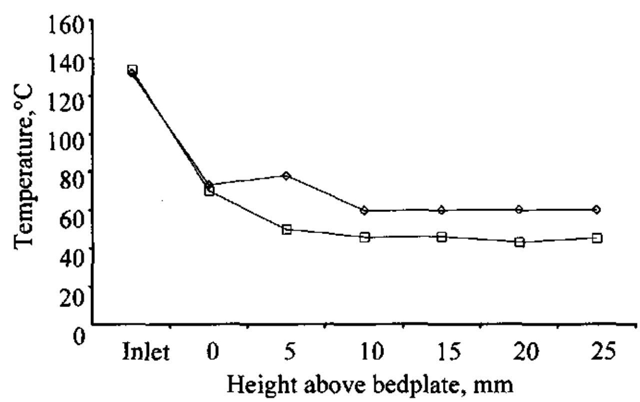

Fig. 6.5. Relationship between temperature and height above bedplate in two positions in the first stage of a fluidized-bed dryer; *◊, position 1; □, position 2*

There are several methods of measuring bed loading at a given weir height, all of them subject to different limitations. Johnson (1989) stopped all airflow while the dryer was working normally, then swept the material from the bedplate and weighed it. This will underestimate the load at the wet end particularly, as the wet dhool is drying during the time the airflow is dissipating up to the time the dhool is weighed. A load range of 13 – 55 kg/m^2 of bed was reported but with no indication of weir height.

Measurements on the pilot scale dryers with the method above yielded a value of 6.0 kg/m^2 with a weir height of 25 mm. The alternative method used involved placing a cylinder or rectangular duct of sheet steel, with both ends open, on the bedplate with the dryer in operation while avoiding disturbance to the bed. Then a flat plate may be slid below the open-ended container to extract the material in a known area. An alternative is to place a piece of wire mesh of open area considerably greater than that of the bedplate, over the bedplate and under the fluidized material. Then with the dryer operating normally the open-ended collector is placed on the mesh, and the two removed from the dryer together. This method is less subject to evaporation errors but is susceptible to errors in collection. Values obtained on the same dryer on the same day with similar feed material gave a mean value of 10.3 kg/m^2 with a standard error of 0.6. The value used is 10 kg/m^2 for a 50 mm weir, or 0.2 kg/mm weir height.

6.6 Simulation results

The output from the simulation model is shown in Fig. 6.6 and Fig. 6.7 for a three stage continuous fluidized bed dryer under typical operating conditions. The dryer is shown starting with no load on the bed, and a constant feed rate. Once the dryer has stabilised, a step increase of 5% in feed rate is imposed at 2000 s elapsed time.

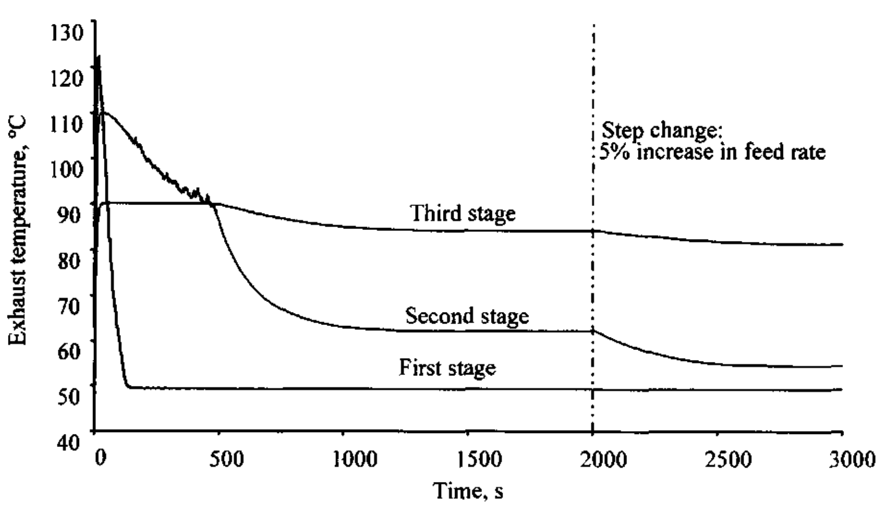

Fig. 6.6. Simulation of continuous three stage fluid bed dryer: exhaust temperature at the end of each stage

The simulation starts with an empty bed. The inlet temperatures are set to 120, 110 and 90°C. As a consequence of the empty bed the temperatures rise in the first period close to inlet temperatures because very little water is being evaporated. Then as the bed load increases more water evaporates and the temperature in each section in turn falls. In the first section, the temperature falls rapidly to a value close the saturation conditions of the inlet air. In the second section, the drop is more gradual because less water is being evaporated. The fluctuation in the temperature of the second stage for the first 500 s is result of a complicated switching procedure which checks whether discharge starts or not. After 500 s the bed is completely loaded and discharge is steady; now the switching procedure causes no more problems. Figure 6.7 shows that at the moment discharge has started the system is not yet in steady state. That is a result of the fact that until 500 seconds the load on the bedplate is increasing; once discharge has started then it has to stabilise from this situation. The temperature in the first section reaches a value close to saturation, while the temperature in third section remains close to the inlet temperature of that section. This is the result of the low evaporation rate in the third section.

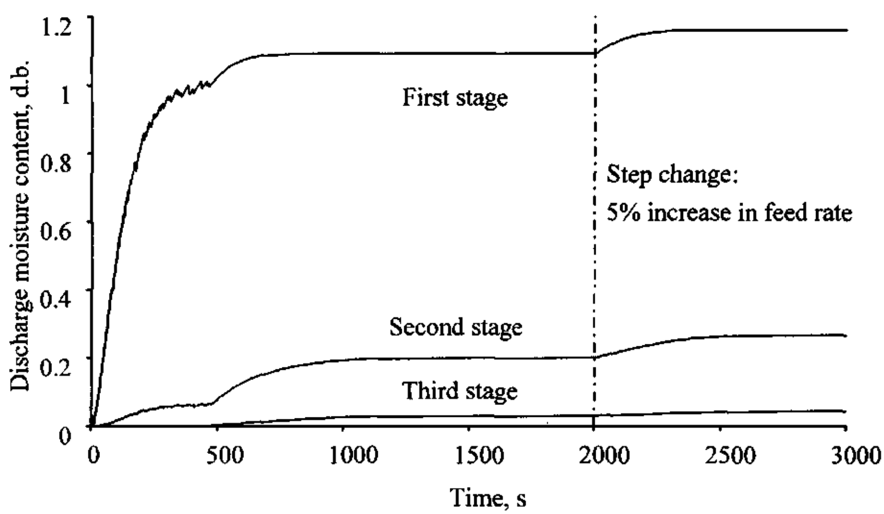

Fig. 6.7. Simulation of continuous three stage fluid bed dryer: bed moisture content at the end of each stage

The step change hardly affects the first stage temperature because it was already close to saturation. The moisture increases and hence the second stage starts to evaporate more water, resulting in a lower exhaust temperature. The extra evaporation is not enough to obtain a constant moisture content after the second stage, so the third stage also starts to evaporate more which results in a slightly lower exhaust temperature and a higher moisture discharged from the dryer.

A simulation of batch drying is shown in Fig. 6.8. For batch drying, a single stage is used as the system is well mixed. The feed rate is set at zero, and the starting load of dry matter and water is used to initialise the integrators.

In this graph, although a single falling rate drying equation is used, a constant drying rate can be observed for the first 80 seconds of the run. This can be seen to correspond to an exhaust temperature close to saturation, indicating that the constant rate phase is imposed by the evaporative capacity of the air rather than being a property of the material being dried. When the air flow rate is increased to higher values the water will be diluted in the air and then the observed constant rate period will disappear.

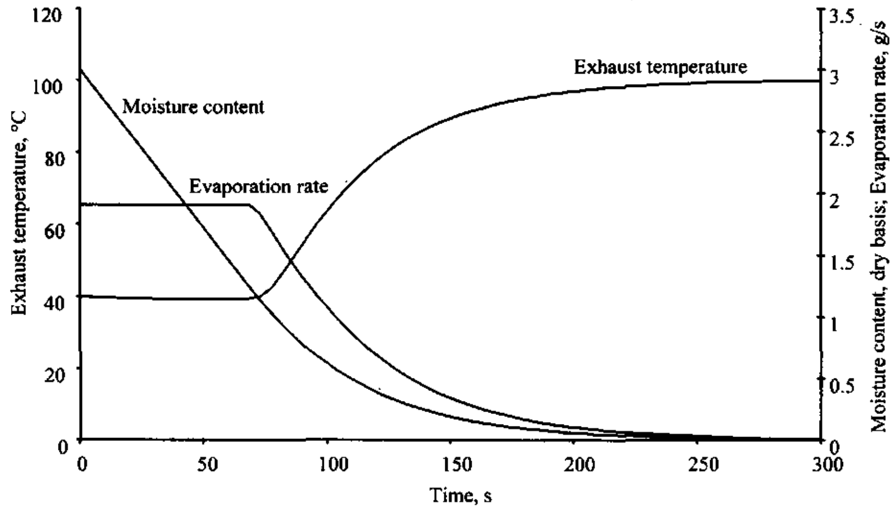

Fig. 6.8. Simulation of batch drying showing moisture content of tea, evaporation rate and exhaust air temperature

6.7 Experimental validation

The model was validated first on the thin layer drying apparatus, and the results gave an excellent fit (Temple & van Boxtel 1999c).

A batch fluidized bed dryer (Fig. 6.9) was then used, based on the apparatus used for fluidization studies (Temple and van Boxtel 1999b). For this application, the below-bed air flow meter was removed and the sensor upstream of the heating elements used to determine the airflow at ambient conditions. The inlet temperature and airflow were controlled by a microcontroller-based system, which also performed data logging functions. For the purposes of model validation, the inlet temperature was set to a constant value, and the airflow decreased slightly with time to allow for the change in fluidization properties with drying. A vibrator was added to ensure fluidization at the higher moisture contents, operating at 10 Hz and approximately 1 mm stroke. Above the bed the parallel duct was replaced by a short parallel section and an expanding section, to rapidly reduce the airflow velocity and deposit material which would otherwise be eluted from the bed. The heater used eighteen 1 kW bar fire elements, switched in groups of 3 elements, 6 elements and 9 elements in a pseudo-binary fashion for energy regulation.

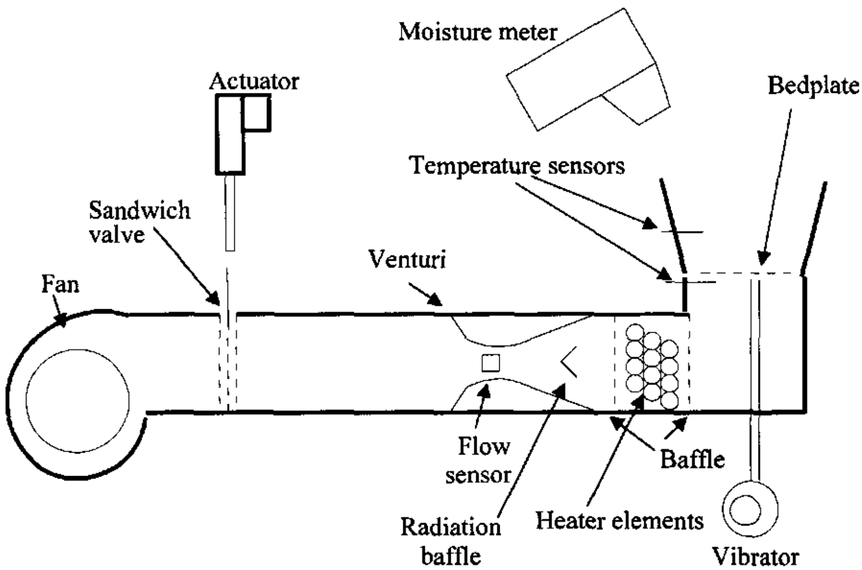

Fig. 6.9. Schematic diagram of batch fluid bed dryer

To monitor the moisture content during the drying process, an infrared moisture meter was calibrated for use over a wide range of moisture in tea, and aimed at the bed. Water cooling and air purge of the window were used to avoid damage to the instrument from the exhaust air, and to stop eluted fibre from confounding the results. It was not possible to use conventional methods, as sampling to obtain sufficient results would have changed the bed load to an unacceptable degree. Two calibrations were programmed into the instrument, one of which gave the best fit over the whole drying range, and one giving a better fit for moistures under 10%. Values from the wide range calibration were logged with the other data from the test rig, being airflow velocity, inlet temperature, exhaust temperature and number of electric heater elements turned on. Data were transferred from the data logging system to a computer, and average readings for a 10 s period recorded for every 10 s interval.

Because the temperature and airflow were not constant, particularly as the system was loaded with dhool and the system back pressure was increased suddenly, the simulation of the run used the actual temperature and airflow data recorded from the run. The starting dhool load and moisture content was used to initiate the integrators, and the exhaust temperature and dhool moisture content were compared with the measured values.

The initial values did not match well once the air had moved from saturation. However, it was not expected that the fluidized bed would behave in exactly the same way as a thin layer; a fluidized bed loses efficiency through bubbling fluidization in some areas and slumping of small volumes of material on the bedplate. A factor to account for the loss in efficiency was tested and incorporated into the drying equation. A value of 0.6 was found to give an acceptable fit over 30 test runs with a range of inlet temperatures from 70°C to 140°C and loads ranging from 300 g to 600 g.

The differing performance between thin layer and fluidized bed drying was summarised by Kunii and Levenspiel (1991). They stated that the mass transfer coefficient for the bed depends on the model of fluidization used (*e.g.* fine particle bed or bubbling bed). They continue "Where the model closely matches the flow conditions in the bed (for large particle cloudless beds), the bed coefficient should match the single particle coefficient. Where it does not, these coefficients differ. This is the case for fine particle clouded bubble beds." Therefore if the bed in a tea dryer was effectively a large particle, cloudless bed the thin layer model would apply directly; this type of fluidization does not occur with the particles of tea so the model must be modified.

Although many researchers describe a constant-rate drying phase with tea, the thin layer experiments could only demonstrate a single falling rate phase (Temple & van Boxtel, 1999c). A constant-rate drying phase appears with the batch fluidized-bed drying experiments (Fig. 6.10). Looking at the temperature profile, it can be seen that the constant rate phase occurs when the air is saturated; in thin layer drying there is more air per unit mass of tea and this phase is not seen. The constant rate phase is therefore not a property of the drying of the tea, but of the air becoming saturated. If enough air is supplied, the constant rate phase disappears but this is not possible with other than a thin layer.

The correspondence of the measured and predicted values can be considered good as shown in Fig. 6.10; the errors are probably due to the imperfect mixing of the bed, where some material dries before the other. The moisture meter only samples an area of about 20 mm diameter, and the exhaust air sensor only measures one point. The drying material moves around the bed, and zones with fibre floating on top can be clearly seen during experiments; this is reflected in the curve for actual moisture content between 150 and 280 s. The predicted exhaust temperature rises from saturation more sharply than the actual value, showing that the assumption of perfect mixing is not true in practice.

Towards the end of the run, the mixing is more effective, and the actual and predicted moistures converge. The predicted temperature is found to rise more rapidly than the measured value at the end of the run, because no term has been included in the model for the specific heat of the dryer structure. A second factor introducing errors at this stage is the radiant energy loss from the hot tea particles to the surroundings above, and the cool air drawn into the bed by natural convection. This effect is also found to affect the temperature readings at the end of a continuous dryer.

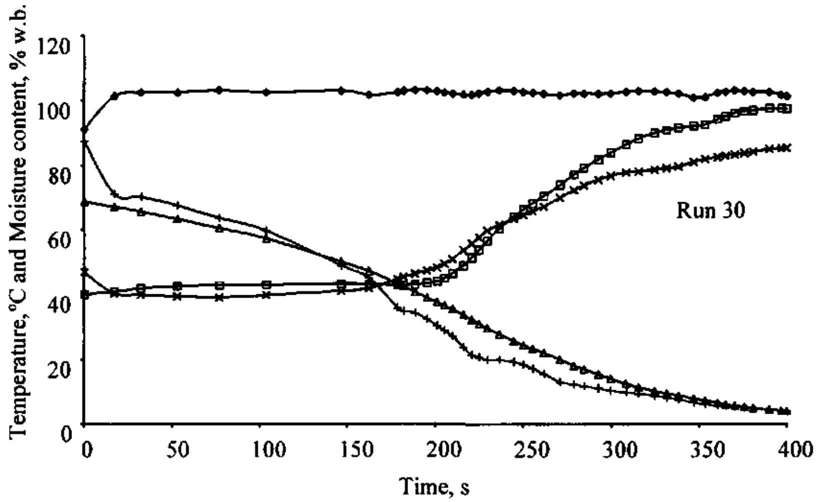

Fig. 6.10. Measured and predicted values from batch fluid bed dryer: *◊Inlet temperature; □predicted exhaust temperature; Δpredicted bed moisture content; × measured exhaust temperature; +measured bed moisture content*

The model was extended to a three stage continuous dryer, as often found in practice, and divides each stage into three subsections. If there was perfect plug flow, an infinite number of subsections would be needed for perfect simulation, and if each stage was well mixed, only a single subsection would be needed. The use of three subsections was an attempt to simulate the balance between perfect mixing and perfect plug flow, and matched the maximum number of temperature measurement points found in practice.

Measurements were taken on a commercial dryer at the Lauderdale factory of Eastern Produce Malawi Ltd. in Mulanje, and on a pilot scale continuous dryer at the Manufacturing Research Facility (MRF) of Tea Research Foundation (Central Africa). The results of the measurements and simulation are shown in Figs. 6.11 and 6.12. The low final measured exhaust temperature in Fig. 6.12 is due to cold air being drawn into the dryer over the weir by the exhaust fan. More sets of actual and predicted values for the MRF dryers show a similar accuracy of prediction. For all these data sets, the efficiency factor used was 0.6, the same as with the batch dryer.

Any discrepancy between the actual and modelled values is likely to come from the sampling and measurement errors on a continuous dryer where sampling is not easy. Operation is rarely as stable as achieved in the simulation, due to erratic feed, fibre causing poor fluidization, and other real world confounding features. It should be noted that validation of the model on continuous dryers was only carried out during steady state operation; response to input transients was not validated.

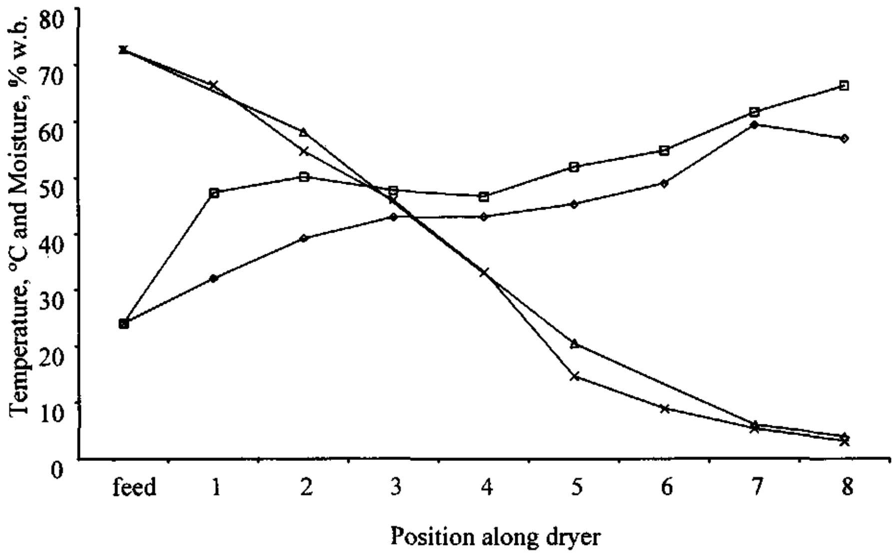

Fig. 6.11. Measured and simulated dryer profile, Lauderdale factory dryer no 1 (see Fig. 6.1 for measurement positions), ***◊ measured temperature; □ predicted temperature; Δ measured bed moisture content; × predicted moisture content***

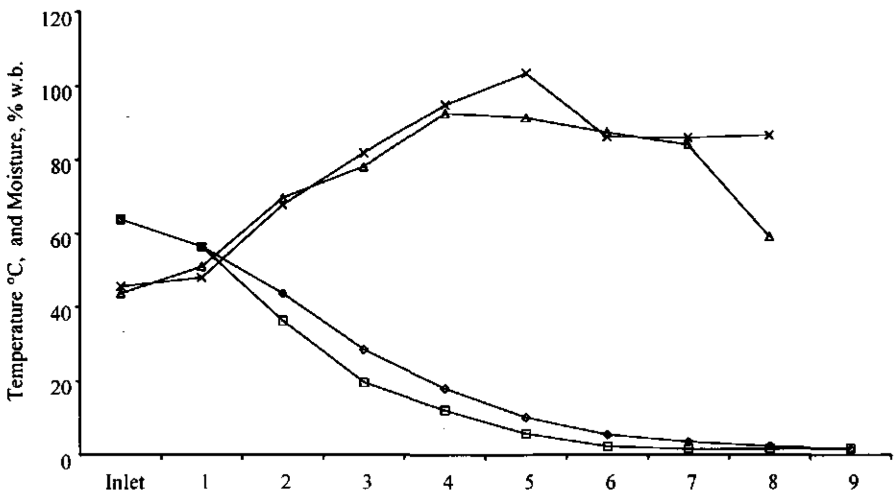

Fig. 6.12. Actual and simulated dryer profile, Manufacturing Research Facility dryer no 2, weir height 25 mm. (see Fig. 6.1 for measurement positions), ***◊ predicted bed moisture content; □ measured bed moisture content; Δ measured temperature; × predicted temperature***

6.8 Conclusion

A model has been developed, based on differential equations and drying properties of tea. The model takes account of equipment dimensions and models the changes in the air used for drying.

The model can be used for simulation of batch drying, and for continuous drying it is able to simulate the start-up phase of operation. Simulations have been carried out to illustrate the characteristics of various types of dryer, demonstrating that the model has broad application.

The model has been validated experimentally on thin layer drying, then on fluidized batch and two types of fluidized continuous dryer. Initially there was a substantial deviation with the fluidized bed type of dryer, probably caused by the value of the drying constant which was extrapolated from non-fluidized data. Correcting the drying rate with an efficiency factor of 0.6 gave a good correspondence between model and factory scale dryers.

Simulation and validation shows that the constant rate drying phase is shown to be a property of the drying air rather than the material being dried.

6.9 Acknowledgements

This study was partly financed by European Union Stabex funds provided to Tea Research Foundation (Central Africa) for a project on Automation of Tea Processing.

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6.11 Appendix – Air and other properties.

Atmospheric pressure at sea level	101.325	kPa
Specific heat of tea (Yoshitomi 1987)	0.96	kJ/kg.°K
(Hongfan Yin 1985)	1.44	kJ/kg.°K
Specific heat of water	4.18	kJ/kg.°K
Specific heat of air	1.011	kJ/kg.°K
Specific heat of water vapour	1.805	kJ/kg.°K
Latent heat of water	2501	kJ/kg
Base temperature for enthalpy calculations	0	°C

7 Controller design and tuning*

7.1 Abstract

Variations in moisture content of dried tea are considerable, hence the moisture control of tea dryers needs to be improved. An experimentally validated simulation model of a continuous fluid bed tea dryer was used to design a control system. Feedback from moisture sensing was found to give good results, but a predictor removes some of the effects of lag in the system. As an alternative to the high-cost moisture measurement, the use of exhaust temperature sensing in the feedback is evaluated. Direct feed back of air outlet temperature at a position two-thirds distance along the dryer does not provide effective control, but with use of inferential control good results are obtained. Normal disturbances in feed rate of 5%, which caused an increase in discharge moisture (wet basis) from 3% to 4.5% without control, were restricted to an increase to 3.4% moisture with direct feedback of exhaust temperature. This control error is eliminated by the use of an inferential estimator, which enables control of the discharge moisture by using only a temperature measurement.

7.2 Introduction

The majority of black tea produced in Southern Africa is dried in fluid bed dryers. During the drying operation a significant amount of energy is consumed, and high drying temperatures or an excessive residence time may compromise tea quality. The feed of the dryer is a more or less constant flow of macerated and fermented tea shoots, known as "dhool", with a moisture content in the range 68 to 75% m.c. w.b. The acceptable range for dryer output moistures is 2.5% to 3.5%. This is well below the maximum moisture allowed for packed teas, but during the sorting and packing stages the tea can pick up enough moisture to take it from 3% to well over the acceptable level of 7%. The main disturbances to the dryer are changes in feed, in terms of quantity and moisture content. Particular problems arise with starting and stopping of the fermenter flow, changing fermenting time and changing of the feed rate into the previous fermenting stage.

In practice, it is not easy to maintain a consistent moisture content out of the dryer, as shown by a factory survey in Sri Lanka (Kandappah and Samarasingham 1991) of 23 factories. The mean values of moisture content and the standard deviations are illustrated in Fig. 7.1.

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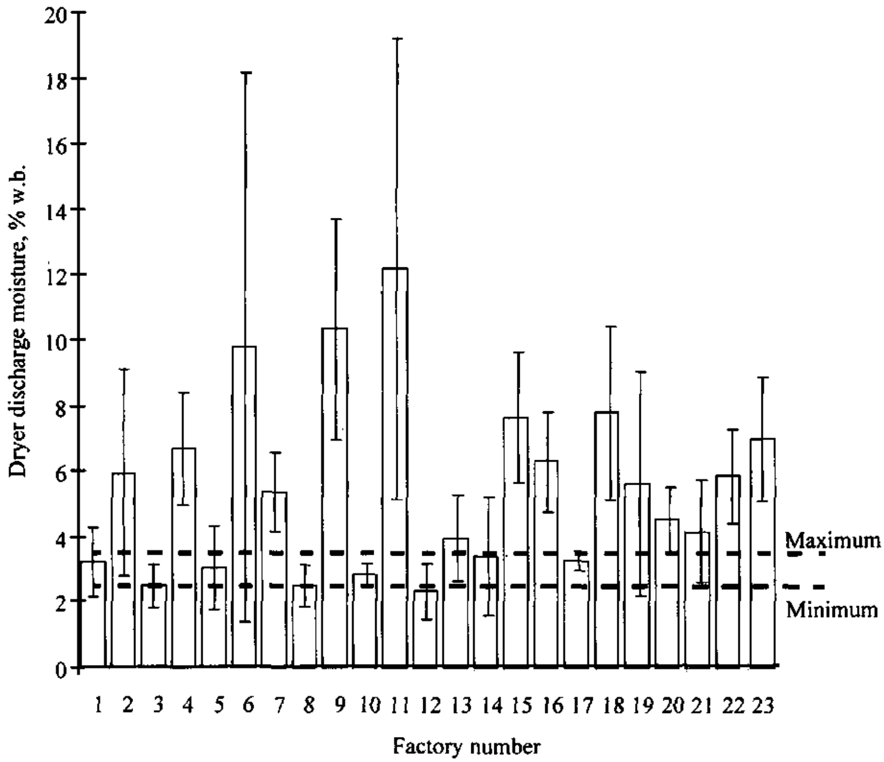


Fig. 7.1. Sri Lanka factory survey: dryer discharge moisture contents (bars) and standard deviations (lines) compared to the acceptable maximum and minimum values (data from Kandappah & Samarasingham (1991))

Only six out of the twenty-three factories had a mean moisture in the normally accepted range of 2.5 to 3.5% m.c. w.b., and only factory no. 17 maintained an acceptable standard deviation of less than 0.5, with factory no. 10 being very close to specification. Most factories failed to dry adequately, and had a very wide spread of dryer discharge moistures.

It is clear that there is need for improved dryer control, bringing benefits in terms of improved consistency of product and reduced energy consumption. However the dryer is not a simple system, and the best method of controlling it is not obvious.

There are two aspects to achieving good operational performance in practice. As well as the design of the controller, the equipment needs to be designed and operated in the correct way in order to have adequate reserve drying capacity to handle the demands of the control system. This paper concerns the design of the controller, which is restricted in the sophistication possible in the environment and remote location of most tea factories.

Interruptions and variations in feed rate to and within the fermenting unit cause variations of the dhool feed rate to the dryer. Development of in-line measurement devices and automation of tea processing units is of recent date and there are no reliable devices available to detect the dhool feed rate variations. Measuring the moisture content of fermenting dhool by near-infrared (NIR) means is confounded by the variation in chemical constituents during the fermenting process. Therefore feed-forward is not an option and feedback control from a discharge moisture content indicator is the main option to improve the performance. Also, it is not commercially attractive to monitor the moisture of the tea being discharged from a dryer continuously; instruments based upon NIR-methods are available but are so costly that they would be difficult to justify financially. Some simpler and cheaper sensor is required as a measure of the drying operation. In this study a simulation model, previously developed by Temple and van Boxtel (1999a), will be used to examine the response of a dryer to various stimuli, to test various control strategies and to investigate possible measurements. The model was validated on a research batch dryer, the three stage semi-industrial continuous dryer of the Tea Research Foundation (Central Africa), Malawi, and a full scale commercial dryer (Temple and van Boxtel 1999a).

7.3 Dryer configuration

There are many different fluid bed dryer configurations; a representative system is shown in Fig. 7.2. The wet dhool is fed into one end of the machine, and the dry tea discharges over a weir at the opposite end. The weir height may be adjustable and regulates the bed loading, and hence the residence time. The air supply is split into three sections, with the hottest air meeting the wettest dhool. The exhaust temperature rises as the tea dries, despite the lower inlet air temperature at the dry end. The constraint on the system is to avoid tea particle temperatures, and thus exhaust air temperatures greater than 90°C.

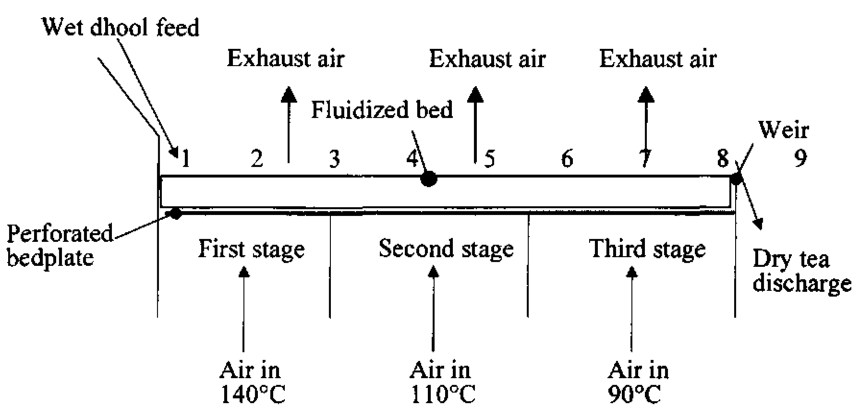


Fig. 7.2. Continuous fluid bed dryer schematic diagram. Numbers indicate temperature measurement positions.

The dryer configuration used for modelling was as validated on a research installation and in practice on the semi-industrial dryer of the Tea Research Foundation and a full commercial dryer (Temple and van Boxtel 1999a). The development of the control methods will be based upon the semi-industrial dryer of the Tea Research Foundation; the settings of this installation are listed in Table 7.1. The following observations arise from the results of the modelling and operational considerations.

Table 7.1. Conditions for simulation as used on the Manufacturing Research Facility Pilot scale dryer.

Feed rate	3.42	kg/min
Feed moisture content	71	% w.b.
Wet end inlet temperature	130	°C
Mid inlet temperature	110	°C
Dry end inlet temperature	90	°C
Wet end air velocity	1.2	m/s
Mid air velocity	1.0	m/s
Dry end air velocity	0.9	m/s
Altitude (above sea level)	650	m.a.s.l.
Ambient dry bulb	30	°C
Ambient wet bulb	26	°C
Dhool feed temperature	27	°C
Weir height	50	mm
Bed area per section	0.72	m^2

The main disturbances to the dryer performance are variations in feed rate and feed moisture content. Variations in feed rate have the greatest effect on the performance of the dryer; dhool moisture variations having a minor effect and occurring much more slowly. This paper concentrates on countering disturbances in feed rate.

There are several variables that may be manipulated to achieve a constant moisture output: dhool feed rate, dhool feed moisture (affected by the withering stage), airflow in each stage, air inlet temperature in each stage, and weir height.

Dhool feed rate and moisture are determined far upstream of the dryer, at maceration and to a lesser extent at fermentation, which happens between 1 and 2 h before drying. This is not suitable for dryer control, as the time lags are too great. Air velocities are set within narrow limits by fluidization requirements (Temple & van Boxtel 1999b) and can not be varied by a control system. Weir height does not have a direct effect on the operation of the first stage, has a marginal effect on the second stage and has an uncertain effect on the third stage. The first stage inlet temperature is generally limited by the maximum output of the heating system, and the last stage temperature is restricted by quality considerations. The second stage inlet temperature remains as the most suitable variable to control (see Fig. 7.3).

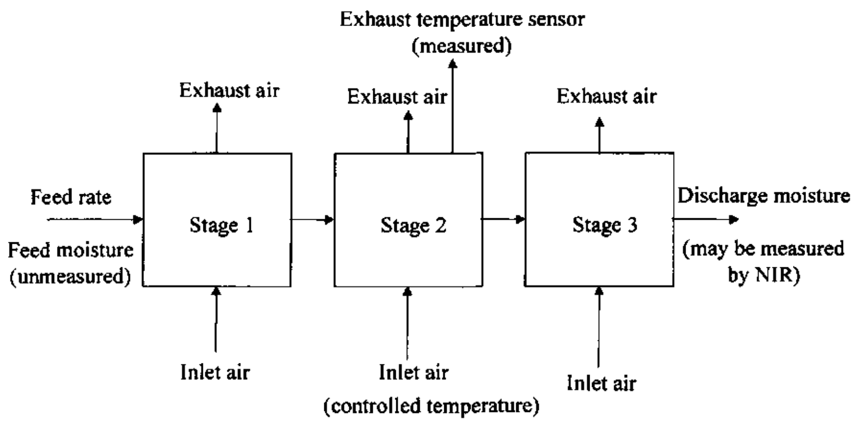


Figure 7.3. Block diagram of dryer

The ideal measurement on which to base the control system is the moisture content of the product delivered, as this is the variable to be controlled. Although there are NIR-techniques available to monitor the moisture content, it is not an attractive option; the costs are high relative to labour cost for correcting the moisture content in tea producing countries, and the calibrations are not fully proven. Therefore, a low cost solution is necessary. Control of the exhaust temperature at a certain position along the dryer is considered as an alternative. Simulation of the dryer configuration shown in Fig. 7.2, using the model given in Temple and van Boxtel (1999a), with varying feed rate, gave Fig. 7.4.

These results show clearly that the temperature at position 6 (as numbered in Fig. 7.2), about two thirds of the way along the bed, is most affected by feed rate disturbance. It was also found to be most sensitive to all disturbances except the third stage inlet temperature and the weir height. In practice, these latter are the least likely to suffer variation during drying. This two-thirds point will be termed the exhaust sensor temperature and is illustrated in Fig. 7.2.

7.4 Controller design

With the other inputs held constant, a step change of 10°C increase in the inlet temperature in the second stage was simulated. The responses of the moisture content and the exhaust sensor temperature were determined, to provide the values for tuning a proportional and integral controller according to the rules of Cohen and Coon (Stephanopoulos 1984). Alternative rules from Ziegler-Nichols (Stephanopoulos 1984) require the system to be controlled by a proportional controller only, and the gain to be increased until instability is reached. The settings are derived from the gain at which instability is reached and the frequency of oscillation at that point.

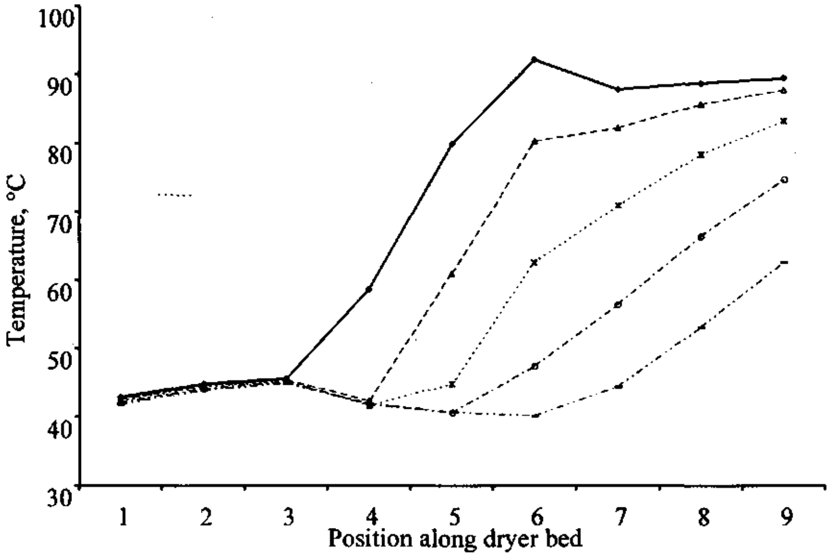


Fig. 7.4. Simulated exhaust temperature response of continuous fluid bed dryer to varying feed rate. ***Feed rate: ◊, 3.6 kg/min; Δ, 4.2 kg/min; *, 4.8 kg/min; O, 5.4 kg/min, –, 6 kg/min. (Feed moisture content 72% wet basis. Discharge moisture contents 0.5%, 1.5%, 3%, 6.5% and 14% wet basis with increasing feed rate)***

The values for the responses of discharge moisture and exhaust temperature to a step change in feed rate and a step change in second stage inlet temperature, both without and including heater lag, are shown in Table 7.1. The Table also shows the Cohen and Coon, and Ziegler-Nichols controller proportional gain and integral time.

The response for the exhaust temperatures at points 6, 7, 8 and 9 along the dryer are given in Table 7.1. Point 6, which was selected on the basis of Fig. 7.4, has a higher gain and a shorter time delay than the other exhaust temperatures, making it most suitable as the basis of a control system.

The controller was first implemented using the discharge moisture content as the measured variable. The temperature range of the control signal was limited to ±50°C of the set point. This is a greater range than is possible in practice in most installations, but represents an extreme that might be possible.

The open-loop response of the system was determined from a 5% increase in feed rate at 1000 s, with all other variables held constant. The moisture content of the discharge was found to rise from 3% to almost 4.5%. A simple feedback controller from discharge moisture to the middle inlet temperature gave excellent control.

In this example, the system is idealised to the extent that the response of the heater unit to a request for increased temperature is assumed to be instantaneous. In practice, there can be a considerable lag as the heater unit and ducting change temperature. The actual response of the heater system for the pilot scale dryers in the Tea Research

Foundation (Central Africa) Manufacturing Research Facility was measured experimentally (data given in Table 7.1, under Heater Response). A control strategy with a Smith predictor is evaluated to compensate for the dead time of this system.

Table 7.1. System responses and tuning parameters

	τ system response time, s	t_d system delay time, s	K system gain	gain units	K_c C & C propnl gain	τ_I C & C integral time, s	K_c Z - N propnl gain	τ_I Z - N integral time, s
Response to +5% feed step								
Discharge moisture	501	19	0.0877	$\frac{\%mc}{kg/s}$				
Exhaust temperature 6	289	11	-45.6	$\frac{°C}{kg/s}$				
Exhaust temperature 7	376	14	-37.4	$\frac{°C}{kg/s}$				
Exhaust temperature 8	439	16	-26.9	$\frac{°C}{kg/s}$				
Exhaust temperature 9	501	19	-17.5	$\frac{°C}{kg/s}$				
Heater response	300	10	1	$\frac{°C}{°C}$				
Response to 10°C increase in inlet temperature section 2								
Discharge moisture	500	10	-0.00083	$\frac{\%mc}{kg/s}$	-54300	32.0		
Exhaust temperature 6	70	1	1.05	$\frac{°C}{kg/s}$	60.1	3.24		
Response to 10°C increase in inlet temperature section 2, incorporating heater lags								
Discharge moisture	635	145	-0.00083	$\frac{\%mc}{kg/s}$	-4849	328	-3600	650
Exhaust temperature 6	620	50	1.05	$\frac{°C}{kg/s}$	10.7	142	43	85
Response to 10°C increase in inlet temperature section 2, with heater lags & Smith Predictor								
Discharge moisture	635	10	-0.00083	$\frac{\%mc}{kg/s}$	-68956	32.3		
Exhaust temperature 6	620	1	1.05	$\frac{°C}{kg/s}$	531	3.32		

During the tuning phase, both Cohen and Coon and Ziegler-Nichols rules were applied. The Ziegler-Nichols rules did not give a meaningful result for the system without heater delay, or with a Smith predictor as delay time compensator. To understand why this happened, transfer functions for the dryer were derived from Bode plots obtained from sinusoidal excitation at different frequencies and an amplitude 10% of the value of the input variable. Typical results are given in Fig. 7.5. As the graph shows, there is a phase shift of -90° for the high frequencies and a high frequency asymptote of -1 suggesting a first order system. In the intermediate range amplitude and phase graphs deviate from a first order system. Therefore fits were made for a second order or higher order system with a lead term. The second order with a lead term option gave better fits to the Bode plots than a first order approach, and shows that the system is second order but acts as a first order.

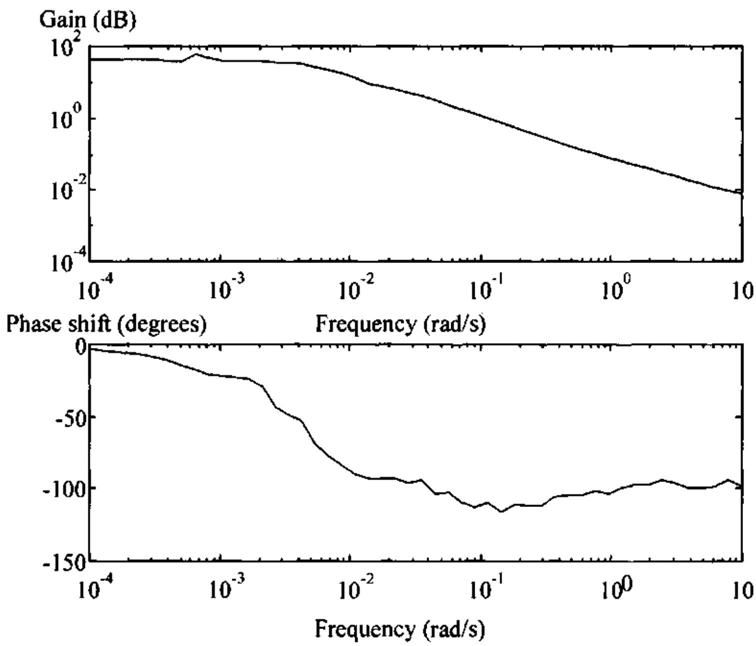


Fig. 7.5 Bode plot of open loop response of discharge moisture content to sinusoidal variation in the second stage inlet temperature (amplitude 10°C).

Because of the first-order-like behaviour of the dryer without heater delay, during Ziegler-Nichols tuning the controller gain can be increased to any value without coming close to instability. The drawback of the Cohen and Coon method was the difficulty of accurate estimation of the small delay time. Despite this drawback the Cohen and Coon approach is a better solution than Ziegler-Nichols tuning.

The Smith Predictor compensates the delay time of the heater. What remains is the first order behaviour of the heater (Stephanopoulos, 1984). Consequently the feedback system controls a first order process (the heater) and a first order-like process (the dryer) in series. For this second order like system with only real poles, the controller gain can be increased without producing instability. Therefore again the Cohen and Coon method is to be preferred.

Both Ziegler-Nichols and Cohen and Coon tuning rules were successfully applied to the system with heater delay and without Smith predictor. The gain and phase margins were examined the two alternative control loops (moisture content control by air temperature and exhaust temperature by air temperature). For the moisture control loop there are greater phase and gain margins with Ziegler-Nichols values than Cohen and Coon while the reverse result was obtained for the exhaust temperature control loop.

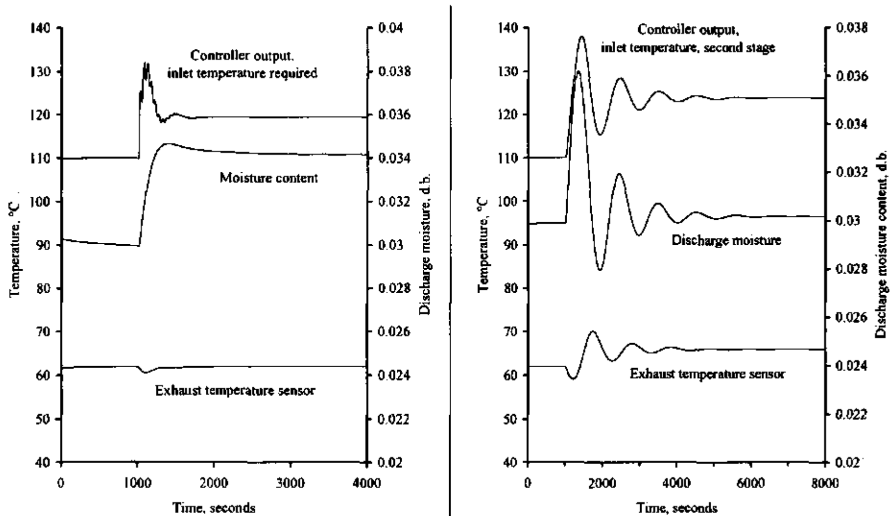


Fig. 7.6 a. Control on exhaust temperature sensor, incorporating heater lag and dead time compensation. Step of 5% increase in feed rate at 1000 seconds.

b. System with inferential controller and dead time compensator, showing the effect of a 5% increase in feed rate at 1000 seconds.

Figure 7.6a illustrates a typical result of the controller using exhaust temperature and with heater delay compensated by a Smith Predictor. The graph shows tight control of the exhaust temperature and also that moisture content does not exceed 3.4%. This value is better than in an uncontrolled situation where for the same disturbance moisture would rise to 4.5%. Direct temperature control helps to reduce the variations in moisture but is not able to cancel them. Therefore, inferential control is used as an extension to the temperature control to remove the remaining deviations (Fig. 7.6 b).

7.5 *Inferential controller*

The principle of an inferential controller is presented in Fig. 7.7a and b. Fig. 7.7a (after Stephanopoulos 1984) describes the dryer by transfer functions from the main disturbance (feed rate) to both output variables (moisture content and exhaust temperature) and the input variable used for control (air temperature to second section).

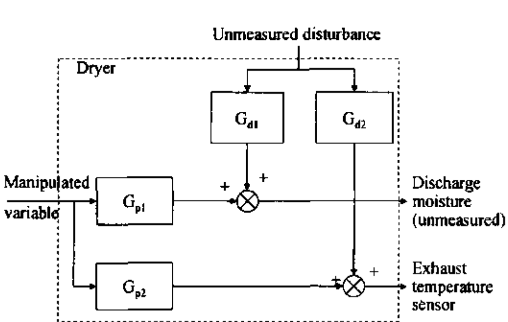
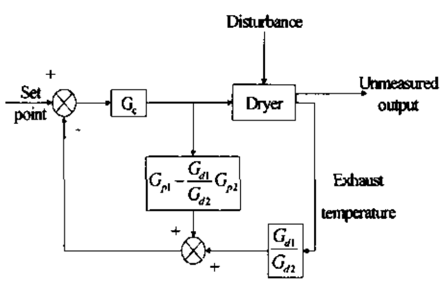


Fig. 7.7 a. Block diagram of process using exhaust temperature sensing.



b. Estimator for inferential control.

Disturbances have influences on the moisture content and the exhaust temperature; each relationship has a different transfer function. If the difference between the transfer functions is small, the exhaust temperature sensor may be used directly to implement a controller. On the other hand, if the difference in transfer functions is significant, then direct control will not be adequate. In this case the four transfer functions are used to estimate the actual moisture content from the temperature sensor output and the controller output as illustrated in Fig. 7.7 b.

The term G_{d1}/G_{d2} in the estimator may be interpreted as translating the temperature signal into a moisture content signal; and the term G_{p1} describes the effect of the control output on moisture. The term $\left(G_{d1}/G_{d2}\right)G_{p2}$ converts the effect of the controller on exhaust temperature into moisture terms. This estimator was constructed using the values in Table 7.1. Controller design was based upon the previous mentioned principles, incorporating the dead time compensator detailed above.

Here the Ziegler-Nichols method was produced the most satisfactory results. Instability set in at a proportional gain of 1700, with the period of oscillation of 195 s. The Ziegler-Nichols method gives a proportional gain of 765 and an integral reset time of 163 s.

A typical response to a 5% step increase in feed rate at 1000 s is shown in Fig. 7.6 b. In this example the inferential controller was only based upon the static gain values of the transfer functions. It gives satisfactory results and can be implemented with minimal demands for the controller. The system provides good control but despite the dead time compensator, it takes some time to settle to the final value. This is not a problem as the deviations during the settling time are minor, and in practice would be averaged when the dry tea is bulked before packing. The response is to a change in feed rate as this is the major factor causing fluctuations in discharge moisture content in practice. It can be seen from Fig. 7.6 b that with the inferential controller, although the control signal is the exhaust temperature, the temperature value is not held constant but the discharge moisture content is maintained.

7.6 Conclusion

Currently technology for tea drying is under development. For better operation and control an exploration of potential control approaches has been made by using a simulation model for a continuous fluid-bed dryer, validated on an commercial tea dryer.

Two options were investigated: first, the direct feed back of moisture content; and second the feedback of an intermediate exhaust temperature. The control performance of direct feedback of the measured moisture content is good but is lowered if the heating system has a significant delay time. To compensate for the effects of lags in the dryer and in the heater system, a dead-time compensator or Smith Predictor is effective.

As the costs for direct moisture measurement are high, the exhaust temperature can be used for the controller feedback signal. This gives good control when an inferential estimator is used.

The improvement in performance using exhaust temperature is acceptable, especially because instrumentation costs are minimal. The control method developed allows improved control of the moisture content of tea discharged from a fluid-bed dryer without requiring sophisticated instrumentation.

7.7 Acknowledgements

This study was partly financed by European Union Stabex funds provided to TRF(CA) for a project on Automation of Tea Processing.

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8 Controller performance under varying operating conditions*

8.1 Abstract

A study was made of the robustness of controllers for fluidized bed tea drying. Several controller configurations have been designed and studied in previous work. Tuning of these controllers is possible using a transfer function estimated from the frequency behaviour of a simulation model under normal operating conditions. In this work a range of operating conditions deviating from the standard conditions was studied. Controller tuning determined by the Cohen & Coon or Ziegler-Nichols methods was not found to be robust over the range of conditions tested. A different method was developed, based on dryer modelling, to establish a range of controller settings giving minimal Integral Squared Error while maintaining adequate gain and phase margins. These settings were found to be suitable for the whole range of conditions tested. A simplification to the inferential controller, using gains only rather than complete transfer functions in the inferential estimator, was shown to be justified.

8.2 *Introduction*

A previous paper (Temple & van Boxtel 2000) on tea dryer control described the development of controller structures for fluidized bed tea drying. In the first instance direct moisture control using a moisture sensor was configured. From step responses it was observed by using graphs that the controller performed well. However, controller performance falls as soon as heater delay become significant. To maintain performance a delay time compensator, as the Smith predictor, was used. As on-line moisture sensors are expensive and difficult to calibrate, a search for an alternative indicator was started. It was pointed out that the exhaust air temperature at two-thirds distance along the dryer was most sensitive to variations in drying performance. Control of this temperature is a good option for reducing the variations in moisture content. However, keeping the exhaust air temperature constant reduces but does not eliminate all variations in moisture content. It was shown that this objective could be realised by using an inferential controller giving a significant performance improvement. The basic concept of the inferential controller is based upon the process and disturbance transfer functions (Stephanopoulos 1984). However, most standard controller hardware cannot implement these functions so an alternative is

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proposed which is based upon the use of only the gains. Such a simplification (ignoring the dynamic parts) could affect the inferential controller performance.

Once a controller was installed on an industrial tea dryer the controller settings would not be changed for a long time. During this period teas with different drying rates have to be dried under different operational conditions. Therefore it is important to know whether the controller will do its job properly over such an extended period.

To evaluate controller performance two main aspects have be considered:

- stability
- accuracy

A practical method to safeguard a controlled system from becoming unstable under the influence of load and disturbance variations is achieved by maintaining sufficient phase and gain margin of the open loop combined transfer functions of the process and controller. For the tea dryer these criteria can be evaluated for the standard tuned controller working over a range of operation conditions and drying rates. For controller performance evaluation, set-point tracking and disturbance rejection are the most relevant criteria. These criteria are derived from the closed loop transfer functions of the controlled process. Moreover, the deviation of the response from the desired value, which can be expressed by the integral squared error, gives a quantitative measure for the accuracy.

To use most of the above-mentioned approaches, knowledge of the process transfer functions is required. However, working with transfer functions implies that a linearised version of the process is used. If the linearisation only represents a narrow range, stability and accuracy cannot be quantified by using the above mentioned methods. Then the best alternative will be the performance test on the dryer in practice using a qualitative measure or the integral squared error (ISE) as a quantitative measure.

This work assesses the performance of the proposed tea dryer controllers using the techniques described above.

8.3 Methodology

Consider a controlled system as given in Fig. 8.1. The closed loop transfer function from set-point to output and from disturbance to the output are given by

$$\frac{y(s)}{y_{set-point}(s)} = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \tag{8.1}$$

$$\frac{y(s)}{d(s)} = \frac{G_d(s)}{1+G_c(s)G_p(s)} \tag{8.2}$$

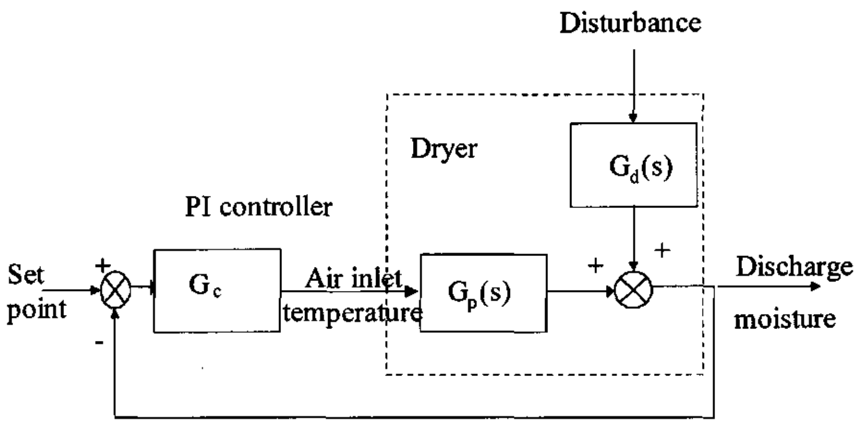

Fig. 8.1 Basic controlled system

For set-point tracking the aim is to keep transfer function 1 close to unity for a wide range of frequencies and for disturbance rejection the second should be as low as possible. Both goals are conflicting so a compromise is required to maintain a minimum gain in the low frequency region and a maximum gain in the high frequency region.

For stability the denominator term of the equations should have negative poles. It is achieved if the product $G_c(s)G_p(s)$, the open loop transfer function of the controlled system ($G_{ol}(s)$), has proper values for the phase and gain margins. The phase margin is the 180° minus the phase value for the frequency where the AR=1. The gain margin is equal to reciprocal of the value of the AR for the frequency at which the phase shift equals to -180°. In standard control practice a design aims for a phase margin greater than 30° and a gain margin greater than 1.7.

As Fig. 8.1 and the equations show, transfer functions of the process are required and have to be derived from the tea dryer model. As the dryer model is programmed in Simulink the tool for linearisation could be used. Attempts to do this failed, caused by the presence of switches (used for different drying phases, and filling the tea dryer) and lookup tables (used for psychrometrics). The spectral analysis tool from Matlab (based on the response to white noise inputs) gave very different values to those given by a series of steady state sine wave excitation trials under the same conditions, so no meaningful conclusions could be drawn. Therefore sine wave responses at a range of frequencies were determined from the process model. This method was successful.

The ISE is defined as:

$$ISE = \int_0^\infty \varepsilon^2(t)dt \tag{8.3}$$

in which ε(t) represents the deviation between set point and realised value. In this work the set point is considered as the value used by the controller, which is in terms of the moisture content of the dry tea when this is the value used by the controller. In other cases, temperature is used, which can be related to moisture content by the inferential relationship.

8.4 Results

8.4.1 Estimating transfer functions

In practical controller tuning, safe phase and gain margins are used in order to prevent the controlled system from becoming unstable from uncertainties affecting the system transfer function. In general, these uncertainties are unknown. However with the availability of a simulation model one source of modifications of the transfer function can be assessed, namely the shifts that occur due to different operating conditions. Table 8.1 shows the parameters of transfer functions of the type given in Equation 8.4 obtained by fitting the sine wave responses under various operating conditions.

The main disturbances that occur in drying conditions are the feed rate and the rate of drying for different batches of tea. Variations in feed moisture content have a significantly smaller effect (Temple et al. 2000) and therefore the effect of this variable is not considered.

To evaluate the controller performance, the transfer functions for different drying rates and feed rates were calculated. As the process is non-linear different operating points and different drying characteristics give other transfer functions. To simulate the controller situation as closely as possible, the transfer functions concern the situation where moisture content is at target (3%) on average while the inlet temperature (normally used as controlling variable) is adjusted to compensate for the changed feed or drying rate.

As an example Fig. 8.2 is selected from the results to show data obtained from the responses for a range of conditions.

The curves were fitted for several types of transfer functions with varying order for numerator and denominator. During fitting the sum of relative error of phase and relative error of log(amplitude ratio) was minimised. The best results were obtained for:

$$\frac{y(s)}{u(s)} = \frac{Kp(\tau_{num}s+1)}{(\tau_{den1}s+1)(\tau_{den2}s+1)} \qquad (8.4)$$

Higher order transfer functions did not give any relevant improvement. Estimated constants for several cases are given in Table 8.1.

Table 8.1: Fitting results for transfer functions over a range of operating conditions. Values in bold text indicate standard operating conditions. The rate factor is a value used to adjust the evaporation rate as measured using thin layer drying apparatus to the rate found in practice with a fluidized bed.

	Rate factor	0.6	0.6	**0.6**	0.6	0.6	0.6	1.0	0.4
	Inlet temperature °C	90	100	**110**	120	130	140	110	110
	Feed rate kg/min	3.155	3.295	**3.42**	3.545	3.665	3.78	3.714	3.095
	Discharge moisture %	3	3.01	**2.99**	3	3.01	3.02	3.01	3
$T_{in}(s)$	Gain K_p	0.847	0.884	**0.9333**	0.943	0.949	0.949	0.436	1.02
to	τ_{num}	34.3	32	**28.44**	24.1	20	17	329	57.3
$T_{exh}(s)$	τ_{den1}	178	176	**164**	163	152	144	954	154
	τ_{den2}	9.32	9.31	**9.51**	9	8.65	8.43	17.7	11.7
Tin(s)	Gain K_p	$-1.1e^{-3}$	$-1.0e^{-3}$	**$-9.7e^{-4}$**	$-9.4e^{-4}$	$-8.9e^{-4}$	$-8.4e^{-4}$	$-1.2e^{-3}$	$-8.9e^{-4}$
to	τ_{num}	94.7	84.4	**73.6**	72.4	69.8	66.9	85.3	89.2
moist(s)	τ_{den1}	240	239	**226**	228	223	219	227	260
	τ_{den2}	240	239	**226**	228	223	219	227	260
Feed(s)	Gain K_p	-36.4	-40.8	**-45.2**	-49.3	-53.2	-64.7	-24	-38.8
to	τ_{num}	92.3	84.9	**78.2**	3.21	3.25	3.08	0	99.2
$T_{exh}(s)$	τ_{den1}	196	183	**172**	298	280	278	389	168
	τ_{den2}	196	183	**172**	4.78	5.25	5.51	30	168
Feed(s)	Gain K_p	0.0755	0.0747	**0.0729**	0.0718	0.0708	0.0702	0.0907	0.067
to	τ_{num}	34.5	140	**126**	109	100	90.1	0.182	0.967
moist(s)	τ_{den1}	504	344	**280**	262	253	243	515	610
	τ_{den2}	39.8	239	**280**	262	253	243	0.321	0.586

From the results it can be seen that the fits for $T_{in}(s)$ to $T_{exh}(s)$ and most values of Feed(s) to $T_{exh}(s)$ gave different values for τ_{den1} and τ_{den2} whereas all values for $T_{in}(s)$ to Moist(s) and most values for Feed(s) to Moist(s) gave $\tau_{den1}=\tau_{den2}$.

In addition to the transfer functions from inlet temperature (controller controlled variable for a controlled system) to outputs, the transfer functions from feed rate to outputs were determined from the model. These are the transfer functions for the major source of disturbances with greatest influence expected for the dryer.

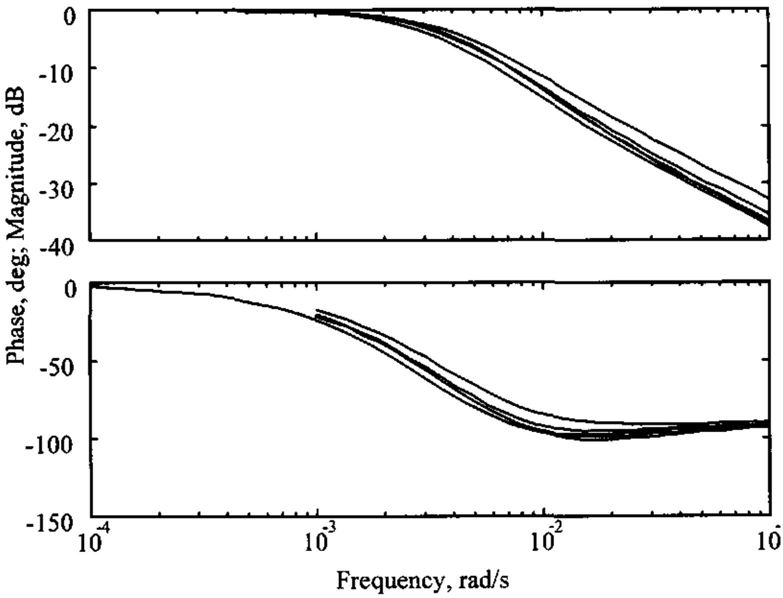

Fig. 8.2 Bode diagram $MC(s)/Tin(s)$ obtained from sine wave simulation for inlet temperature of 90°C (top curve), 140°C (next curve) rate factor 1.0 (middle curve), standard operating conditions (next curve), rate factor 0.4 (bottom curve).

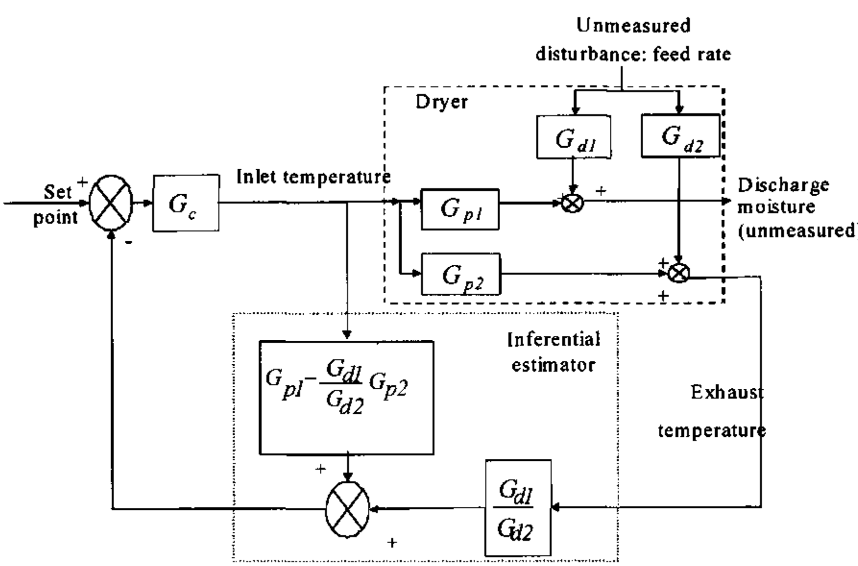

Fig. 8.3 Inferential control scheme

8.4.2 Inferential controller

Before proceeding, a simplification of the fourth controller type, the inferential controller, was tested on the nominal plant. This simplification entails the use of static instead of dynamic compensator blocks as shown in Fig. 8.3. The implementation of these full transfer functions is not possible in most commercial hardware available in tea drying countries. To simplify the calculations, the gains alone can be used instead. Fig. 8.4 shows for both options the differences in Bode diagrams for the response of moisture content to changes in set point and changes in disturbance input.

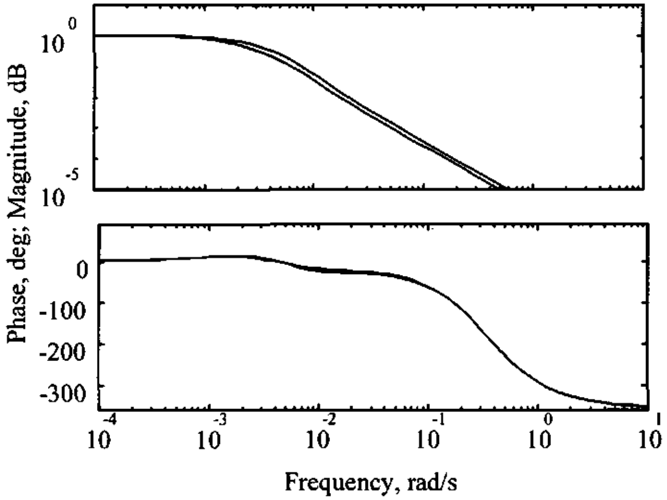

Fig. 8.4a. Set point tracking bode plot comparing full transfer function inferential estimator (upper curve) with gains only estimator (lower curve)

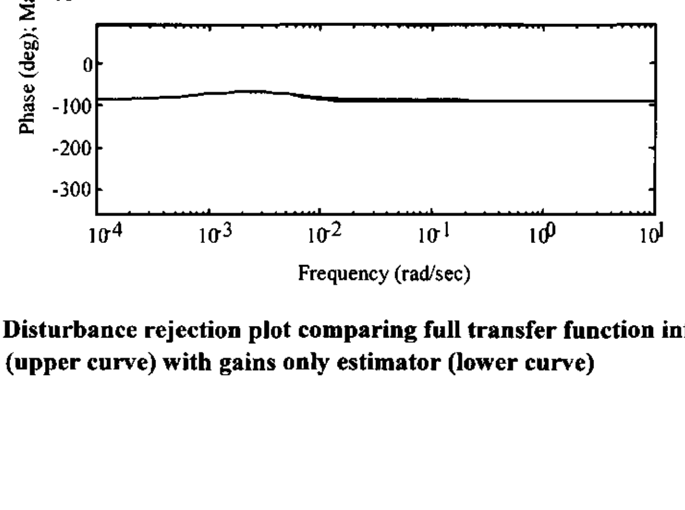

Fig. 8.4b. Disturbance rejection plot comparing full transfer function inferential estimator (upper curve) with gains only estimator (lower curve)

These figures showed very small differences, both for tracking (closed loop transfer from moisture set point to final moisture content) as well as disturbance rejection (closed loop transfer from feed rate to final moisture content). Because of these results, this simplified controller was used in the remainder of this paper.

8.4.3 Gain and Phase margin evaluations for different controller types

The transfer functions for the dryer under various operating conditions were combined with the transfer functions for the controllers, to evaluate the gain and phase margins as operating conditions varied. Tuning the controller configurations for the nominal plant using the conventional methods gave the results shown in Table 8.2 and displayed in Fig. 8.5.

Table 8.2. Controller characteristics

Controller	Tuning	Kc	tau I
Exhaust temperature feedback	C&C	10.7	142
	Z-N	43	85
	new	9	310
Moisture feedback	C&C	-4849	328
	Z-N	-3600	650
	new	-4500	1200
Moisture feedback + Smith	Z-N	31500	129
Inferential	Z-N	765	162
	new	970	325

The final controller, which combined a PI controller with a Smith predictor for delay time compensation and an inferential estimator, was used with the PI values determined by the Ziegler-Nichols tuning procedure. The gain and phase margins under standard operating conditions were not high, with a gain margin of 1.27 and a phase margin of 9.3°. However as the feed rate was varied up or down by 10%, the gain margin did not deteriorate at all, and the phase margin only slightly, the worst value being 8.35° at 3% increased load.

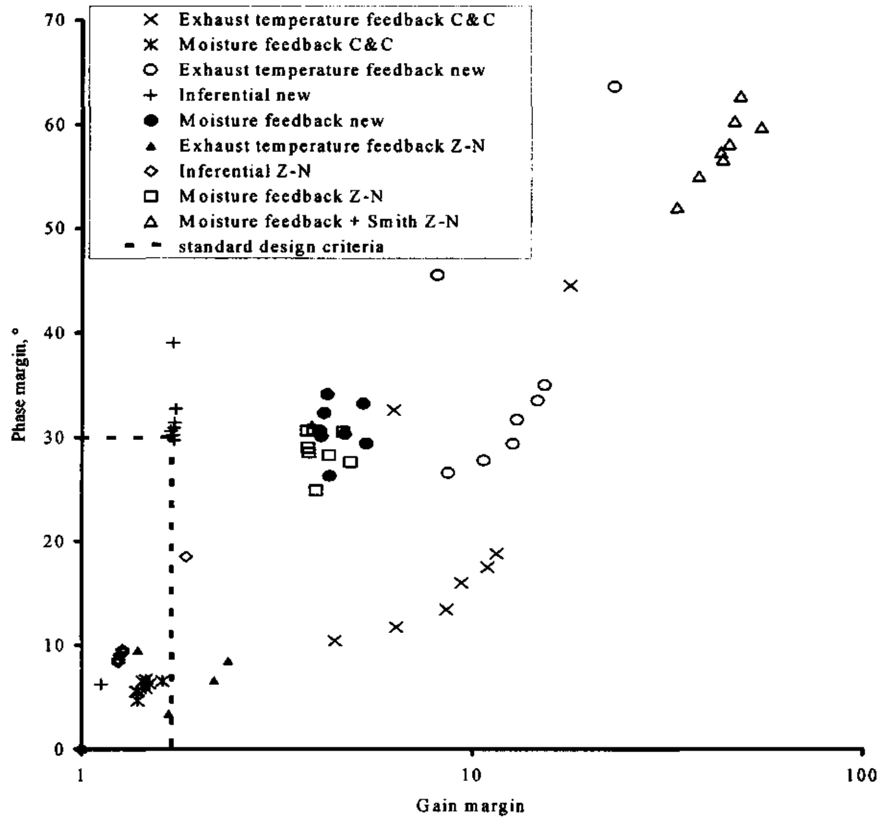

Fig. 8.5 Gain and phase margins for controller settings derived from Cohen & Coon, Ziegler-Nichols and a new method for various controllers under the full range of conditions tested.

Fig. 8.5 shows a summary of results for the range of controllers employed in the development of the final system. The greatest gain and phase margins are from the moisture-controlled system with the Smith predictor and the lowest margins with the inferential estimator taking a temperature signal from the dryer. The simplest control system listed here, using temperature feedback only with no inferential estimator, after a 5% step in feed rate allows the moisture content of discharge to rise from 3% to 3.4%, whereas uncontrolled it would rise to 4.5%.

Two conclusions may be drawn: (i) the actual gain and phase margins may vary considerably over the range of operating conditions for some controller types; (ii) with some controllers the gain and phase margins are unsafe to provide enough robustness against remaining uncertainties in the plant, while for others they are unnecessarily wide, leading to loss in performance.

In order to improve the situation a new procedure is proposed which tries to get as close as possible to phase and gain margins considered safe (30° and 1.7, respectively) while at the same time ensuring the lowest possible ISE. The procedure was performed for the nominal plant. First an automated search procedure was used to identify tuning values that gave the lowest ISE. These led to worse stability values, so an alternative approach was required. A contour plot of gain and phase margin values was then calculated for a range of values of controller gain G_c and integral time τ_I. An additional contour plot of ISE values was calculated for the same values. By overlaying these plots, an area could be determined with gain margin greater than 1.7, phase margin better than 30° and minimal ISE. The results are given in Figs 8.6 – 8.9 and as an overview in Fig. 8.10.

It may be noted that although all the systems investigated are based on the same process model, and modify the controller in different ways, the maps differ considerably (Fig. 8.6 – Fig. 8.9), particularly the plots of ISE values. In the case of the inferential system (Fig. 8.9) the optimum point is defined by both gain and phase margins, while for the other systems the gain margin only is limiting. To keep the diagrams simple, only the major lines for phase and gain margin values have been included. For the moisture feedback system with Smith predictor, the Ziegler-Nichols tuning value coincides with the optimum determined by this method. This does not happen with the other systems considered.

Indeed, for some systems there is no clear optimum value. This is better illustrated by Fig. 8.10, which shows the direction in which the Gain Margin, Phase Margin and Integral Squared Error improve with increasing controller gain and integral time. If the ISE value is in the same direction as one of the margins, and the other margin is close to this quadrant, there will be no clear optimum setting (as is seen with moisture feedback with a Smith Predictor). There will be a clear optimum tuning if the ISE value improves in the opposite direction to the other values, as in the case of the inferential control with Smith Predictor.

Finally, all the controllers tuned using the new method were evaluated over the whole range of operating conditions considered. The selected tuning values are shown in Table 8.2 and the results are illustrated in Fig. 8.5. These are clearly superior to the values obtained from conventional tuning, although some points remain with inadequate phase margin and one point for the inferential controller is well into the danger area.

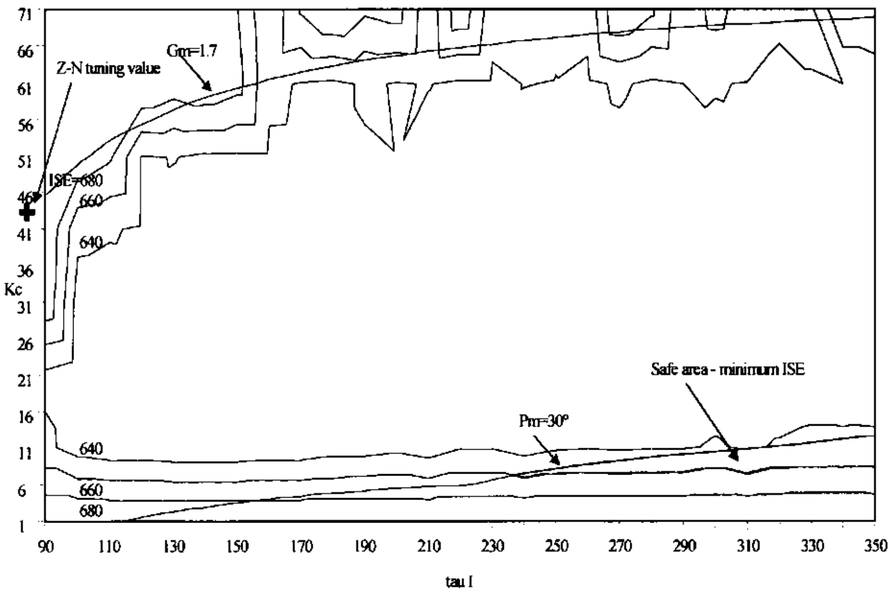

Fig. 8.6 Graphical overlays of gain margin, phase margin, and ISE values to identify suitable controller values for a simple temperature controlled system. The shaded area indicates the location of minimum ISE for phase margin>30°, gain margin>1.7

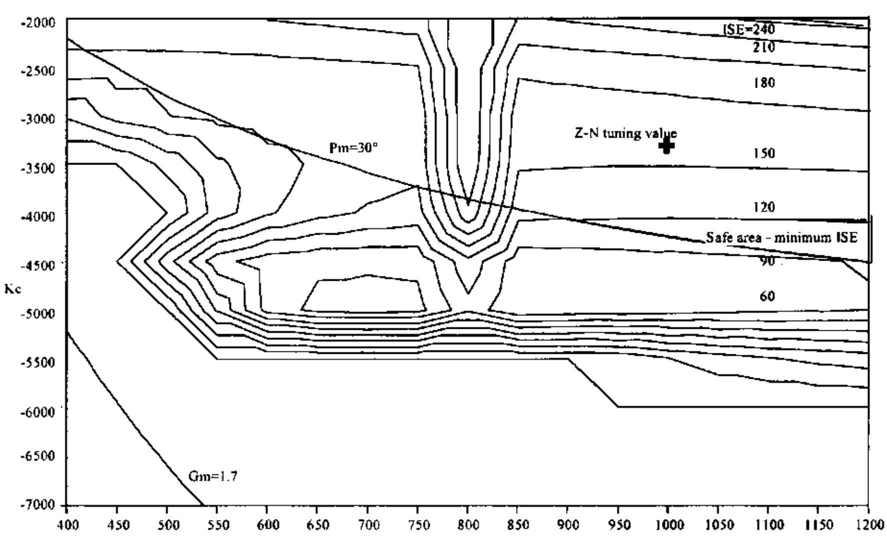

Fig. 8.7 Graphical overlays of gain margin, phase margin, and ISE values to identify suitable controller values for a simple discharge moisture controlled system.

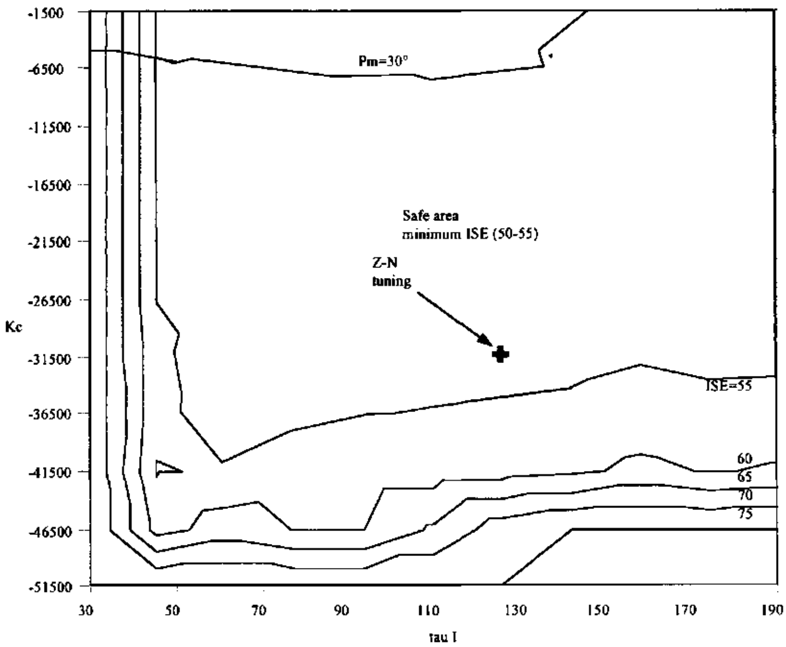

Fig. 8.8 Graphical overlays of gain margin, phase margin, and ISE values to identify suitable controller values for a discharge moisture controlled system incorporating a Smith Predictor.

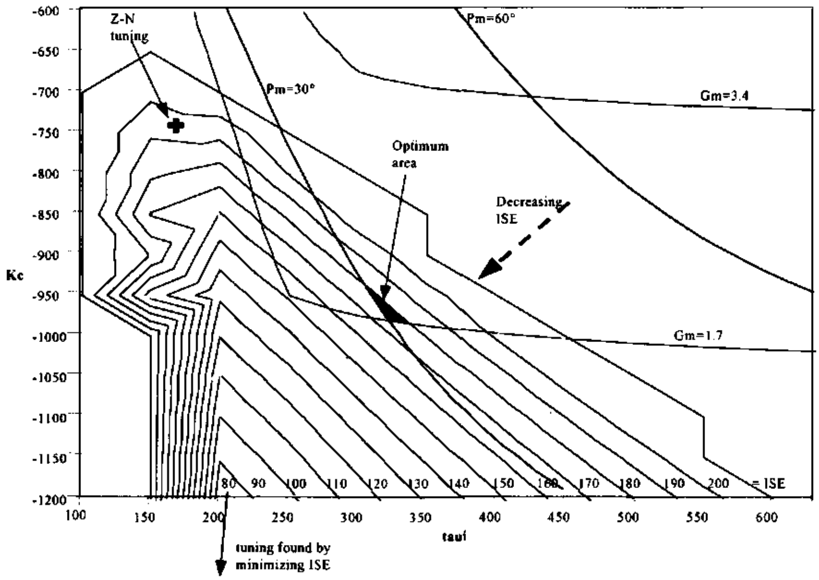

Fig. 8.9 Graphical overlays of gain margin, phase margin, and ISE values to identify suitable controller values for a system incorporating a Smith Predictor and an inferential estimator.

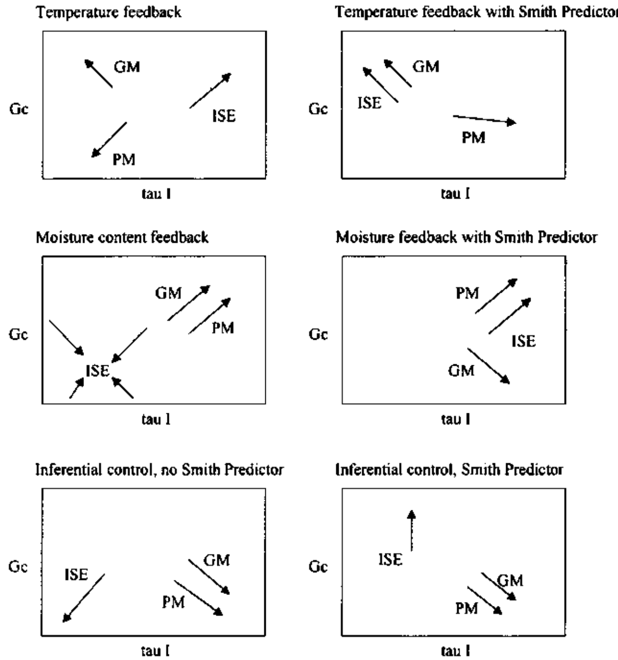

Fig. 8.10 Diagram showing direction of improvement in Gain Margin, Phase Margin and Integral Squared Error for various controllers.

8.5 Discussion

The points plotted in Fig. 8.5 show that over the changes of drying parameters studied, the conventionally tuned systems show variation, sometimes giving a system at the brink of stability and sometimes giving a very high ISE value. The controller values selected by the alternative method are not only the best selected for the normal operating point, but are also robust over the full range of conditions considered. As a consequence, if the conventional tuning methods were to be used, the settings would have to be changed as the dryer operating conditions changed. However, the better tuning achieved by the new method is good enough to handle the full range of operating conditions expected for operation.

The Cohen and Coon tuning method was intended for systems which may be approximated by a first order system with dead time (Stephanopoulos 1984), and the results here demonstrate that this approximation does not hold for the fluidized bed tea dryer. The Ziegler-Nichols closed loop method was intended for systems where the process dynamics are not known, but does not suit processes incorporating integrators (Ogata 1997). These starting-points are probably the reason why under varying operation conditions unsafe margins towards stability were obtained.

The alternative procedure described above can be used to find a controller setting with adequate gain and phase margins, and with the minimum value for ISE (or any other objective function) which can give these margins. However, the procedure requires a model of the system and also a transfer function for the operating point of the system. It would be useful to develop a rule for tuning, to simplify the procedure. This is not possible for the few cases available for study at present. If this work was extended to cover other similar fluidized bed dryers, over a range of sizes and operating conditions, then some generalisation might be possible, leading to the formation of a tuning rule.

To determine phase and gain margins, transfer functions must be used. As these have been fitted to data generated by the model, they are not a perfect representation of the model, which is again an approximation (statically validated) to the real dryer. To ensure that the data are representative, following a phase and gain margin determination, the ISE value should be determined from the model, reducing the degree of abstraction from the validated model. This restricts the use of this method in a production situation to situations where a model can be developed. However, it is relatively simple to use the standard fluidized bed model with dimensions appropriate to any dryer found in commercial practice.

8.6 Conclusions

The inferential estimator using gains only, rather than full transfer functions to provide an estimate of discharge moisture from exhaust and inlet temperature did not result in appreciably different results over the frequency range studied.

For the tea dryer, an inferential controller with just static compensation functions plus Smith predictor gave excellent results.

Investigations into the robustness of fluidized bed tea dryer controllers, with parameters selected by the Cohen and Coon or the Ziegler-Nichols methods show that the tuning is not satisfactory over the whole range of operating conditions expected in practice. A method of selecting controller parameters using mapping of phase margin, gain margin and integral square error to find the controller gain and integral time gave superior results which were satisfactory throughout the operating range.

8.7 Acknowledgements

We are grateful to Rachel van Ooteghem for providing a procedure to estimate transfer function parameters from a Bode diagram.

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9 Control in the context of design and operation conditions*

9.1 Abstract

A simulation model of a continuous fluid bed tea dryer, previously validated, was used to investigate the options for control of the dryer. The variation in heat available proved to limit the possibilities to compensate for variations in feed rate in practical dryers. If dryers operate under limited control power of the air temperatures it is recommended to control the feed rate into the continuous processing system as tightly as possible, and to correct this for other variations in the system such as feed moisture content.

The combination of tight control of moisture together with short residence time for high quality is not possible with current dryer designs, considering the variations in feed rate found in practice.

9.2 Introduction

Previous papers on tea dryer control (Temple and van Boxtel 1999, 2000a, 2000b), discussed aspects of the design of a controller for a fluid bed tea dryer and the robustness of these controllers under varying operation conditions. However, controlling is not only a matter of the design of feedback loops but also a matter of design and operation characteristics. Before a control system with feedback elements, delay compensation and other features can be implemented in practice, a number of other constraints must be taken into consideration. These concern the design of the dryer, the heat source and air supply. To compensate for variations in the moisture there must be enough heat generating capacity to be able to vary the inlet temperature over an adequate range. Moreover, the system will be disturbed by actions that take place upstream in the process, in withering and fermentation. The impact of these disturbances varies and needs feedback compensation to minimise their effects.

This paper attempts to determine some of the limitations on a controller in industrial application, and to determining ways around any such limitations. The use of modelling will enable conclusions to be drawn about potential control systems, which would not otherwise be possible without extensive experimental measurements. The model could be used to look at multiple simulations with the control loop in place; a more systematic approach is to look at the steady state gains, the ratio of input to

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* Submitted to Computers and Electronics in Agriculture as Temple, SJ; van Boxtel, AJB "Control of fluid bed tea dryers: Control in the context of design and operation conditions".

output for various inputs. Then the potential for correction for one disturbance by manipulating another input may be determined.

There are some physical limitations to the dryer inputs. Many dryers operate from radiators, supplied with steam from a boiler rated to operate at 8 Bar, which limits the maximum temperature to about 140°C. A few dryers use the products of combustion directly, from gasified fuelwood, or petroleum based fuels, and a maximum inlet temperature of 160°C might be used if necessary. Those dryers working on radiators often have no control system other than the manual steam gate valves; the direct fired dryers often have thermostatic control of the inlet temperature; some use feedback from the exhaust of each stage to control the inlet to that stage.

The only published work on tea dryer control is by Yin Hongfan *et al.* (1988), but applies to whole leaf tea in a different type of dryer and so is not directly relevant to this study.

9.3 Dryer configuration

There are many different configurations in practice, but a representative system of a fluidized bed tea dryer is shown in Fig. 9.1. The wet dhool (macerated and fermented tea shoots) is fed into one end of the machine, and the dry tea escapes over a weir at the opposite end. The weir height is often adjustable and will regulate the bed loading, and hence the residence time. The air supply is split into three sections, with the hottest air meeting the wet dhool. The exhaust temperature will rise as the tea dries, despite the lower inlet temperature at the dry end. The aim is to avoid tea particle temperatures, and thus exhaust temperatures, of greater than 90°C.

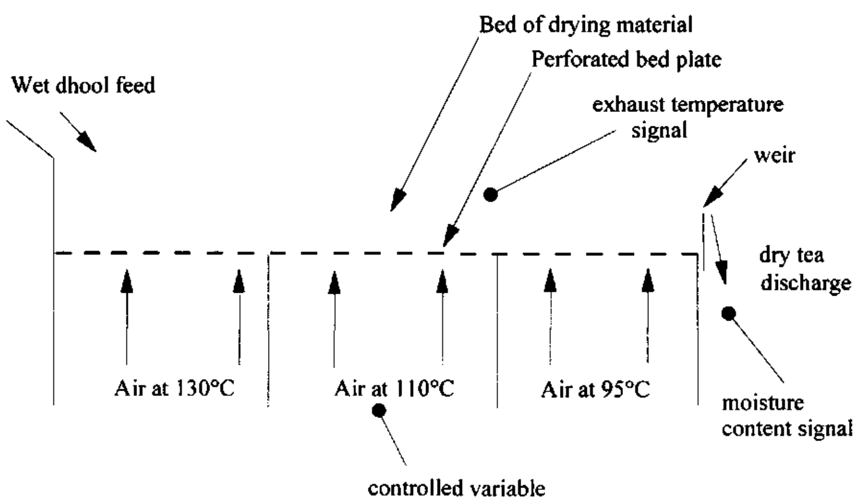

Fig. 9.1 Continuous fluid bed dryer schematic diagram

There are several variables that may be manipulated to achieve a constant moisture output. They are: dhool feed rate, dhool feed moisture, airflow into each stage, air temperature into each stage, and weir height.

The dhool feed rate is dependent on upstream processes. Following maceration, the "fermentation" (enzymic oxidation) stage of manufacture has an optimum duration for quality, after which the drying stage serves to arrest this activity. Therefore the feed rate into the dryer is normally equal to the discharge from fermentation. Some factories are "in-line" with one maceration unit feeding one fermenter and one dryer; others may have say four fermenters feeding a common conveyor which in turn feeds five dryers.

Effectively the feed to the dryer becomes the feed to maceration plus a time delay of between 45 minutes and 2 hours. In addition, as ambient conditions or the type of leaf being processed change, the fermenting time may be changed during the course of manufacture. A source of disturbance to the feed rate is due to breakdowns and short gaps in manufacture of about 5 minutes to separate different types of tea being processed.

The major limit on factory throughput is normally dryer capacity, so this is what will determine the feed rate into the maceration stage.

The moisture content of dhool being processed is determined by the withering stage, before maceration. The moisture content of the fresh shoots arriving from the field may be range from 70% to over 80% w.b., and there may in addition be surface moisture from dew or rain. During withering the moisture content is reduced to a suitable range for subsequent processing. In the Orthodox method of tea manufacture, where the leaves are rolled rather than macerated, withering proceeds to below 60% in order to disrupt the cell structures. For LTP or CTC tea manufacture, the moisture content is normally controlled to between 70 and 72%; in LTP manufacture going outside this range results in a very unsatisfactory dhool consistency. Under extreme weather conditions, manufacture may be carried out down to 68% or up to 74% moisture. During maceration, some moisture may be lost but this is rarely more than 1% so is not significant. Therefore the moisture content of dhool arriving at the dryer may be considered constant for most of the day, and not a variable which can be used to control the drying process.

The airflow in the dryer is set to achieve good fluidization without excessive elution of fines; this is not a setting that can be used for dryer control. The range of superficial flow velocities used ranges from 1.3 m/s down to 0.9 m/s, dependant on the moisture content of the dhool to be fluidized. The range of values suitable for a given moisture content spans less than ± 5% of the airflow, so there is no possibility for using this as a variable to control drying.

The weir height and the degree of expansion due to fluidization determine the amount of material on the bed. The minimum weir height is set by the accuracy of levelling the bedplate, and needs to be at least 20 mm in practice. The maximum is determined by the failure of uniform fluidization at greater bed depths than 75 mm. The lower the weir, the less the residence time of material in the bed, leading to better quality of the end product. Quality is compromised by a low rate of drying allowing the enzyme reactions to continue at the start of the drying process, and by mechanical damage removing the very fine leaf hairs ("bloom") from the particles.

Air inlet temperature remains the only possible controlled variable into the dryer, to compensate for variations in feed rate and feed moisture content. Temperature of the incoming air must be controlled within limits set by the effects on quality of the tea, and the capacity of the heat generating equipment. For drying to proceed with adequate speed to ensure quality, inlet temperatures should be at least 90°C and to avoid quality loss through heat damage, exhaust temperatures should be maintained below 95°C. At the feed (wet) end of the dryer, where the exhaust air is close to saturation, the inlet temperature may be allowed to rise to 160°C without affecting quality; however if the heat comes from an 8 Bar boiler the practical limit will be 140°C. With direct firing, for example by a gasifier, this limit is not present; a flue gas to air heat exchanger may be able to exceed 140°C if designed for such temperatures. Most of those used in tea are designed for about 100°C outlet temperature. At the discharge (dry) end of the dryer, the exhaust temperature is close to the inlet temperature, so the inlet should not be above 100°C.

In order to quantify the "control power" of the heating system the continuous fluid bed dryer model (Temple & van Boxtel 1999) was used to investigate the effects of feed rate and feed moisture content on the temperature profile above the dryer bed, and on the discharge moisture. A set of operating conditions was selected which gave the desired 3% moisture content delivery, and either feed rate or moisture content varied in steps within the normal expected range.

The dryer configuration used was as validated in practice; the settings are listed in Table 9.1. These values used are the same as in previous work (Temple & van Boxtel 2000a).

9.4 Results from simulations

In all the simulation studies, all the parameters in Table 9.1 were held constant apart from the variable under study, which was varied within the available operating range either side of the value in Table 9.1.

The weir height, mentioned above in terms of fluidization, was studied. Figure 9.2 shows that while residence time increases linearly with weir height, the moisture content at discharge varies approximately with the reciprocal of the square root of weir height. It is clear from this result that a weir height in the region of 50 mm is close to optimal, as below this height the loss in moisture removal efficiency is severe, but above this it is marginal while the residence time increases linearly. This weir height also corresponds with the optimal setting for fluidization characteristics.

Table 9.1 Conditions for simulation – Typical operating conditions for Tea Research Foundation Pilot Scale continuous fluid bed dryer.

Feed rate	3.42	kg/min	(range ± 15%)
Feed moisture content	71	% w.b.	(range ± 3% m.c.)
Wet end inlet temperature	130	°C	(range ± 10°C)
Mid inlet temperature	110	°C	(range ±10°C)
Dry end inlet temperature	90	°C	(range ±10°C)
Wet end air velocity	1.2	m/s	(fixed value)
Mid air velocity	1.0	m/s	(fixed value)
Dry end air velocity	0.9	m/s	(fixed value)
Altitude	650	m.a.s.l.	
Ambient dry bulb	30	°C	
Ambient wet bulb	26	°C	
Bed area per section	0.72	m^2	

Varying the dryer loading (varying feed rate for one size of dryer, or applying the same feed rate to a different size of dryer) displaces the line in the y-axis only. The shape of the curve varies slightly, but maintains similar characteristics.

Although from this figure it seems that weir height might be used as a variable to control dryer performance, the effect on the bed is not straightforward, as shown by the temperature profiles given by varying weir height at constant load (Fig. 9.3). Increasing weir height, which reduces discharge moisture, gives a decrease in mid-dryer temperature but an increase in temperature at discharge (position 9).

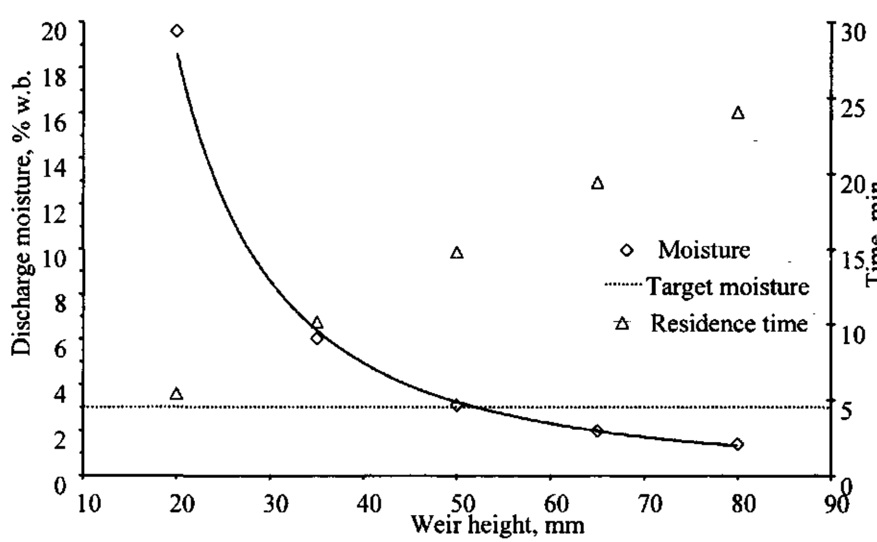

Fig. 9.2 Effect of varying weir height on discharge moisture and residence time

As well as not providing a clear temperature signal, the effect of changing the weir height on discharge also makes it unsuitable for control with a moisture meter. Raising the weir has the effect of stopping discharge for some time until the bed level has risen; lowering the weir results in a rapid discharge of material from the dry end of the dryer, giving rise to some overshoot until stable operation has been resumed.

Figure 9.4 shows the inlet temperatures required to compensate for varying feed moisture content away from the target 71% m.c. w.b. determined by process considerations upstream, to the extremes likely to be found in practice of 68-75%. The value found is from varying only one of the inlet temperatures to compensate; the other two are held constant. It can be seen that the temperature ranges available at each section by itself are enough to handle any variation in feed moisture required in practice, and a control system would be effective for this purpose.

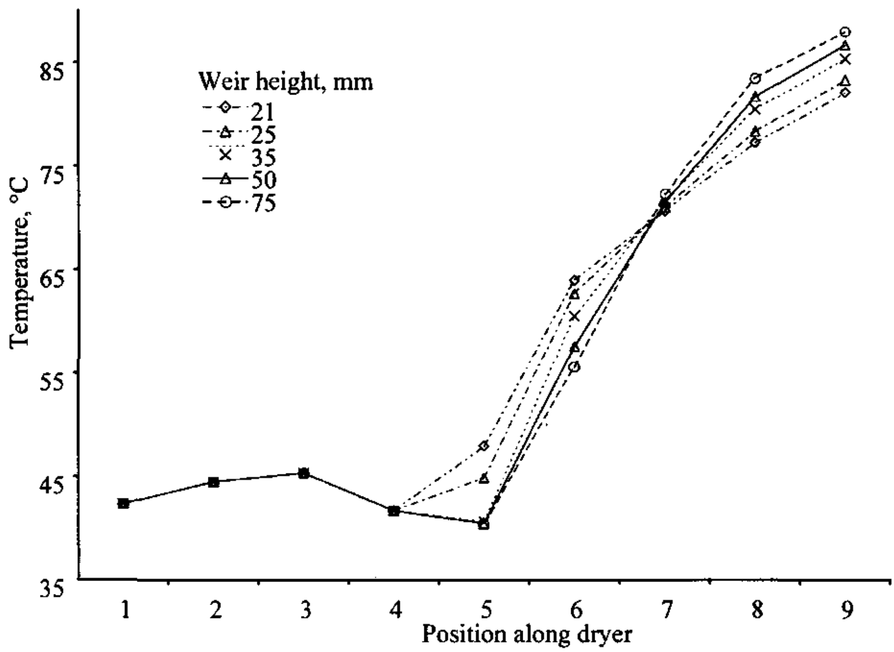

Fig. 9.3 Exhaust temperature profile at constant load and varying weir height.
Position 1 is feed end, position 9 discharge.

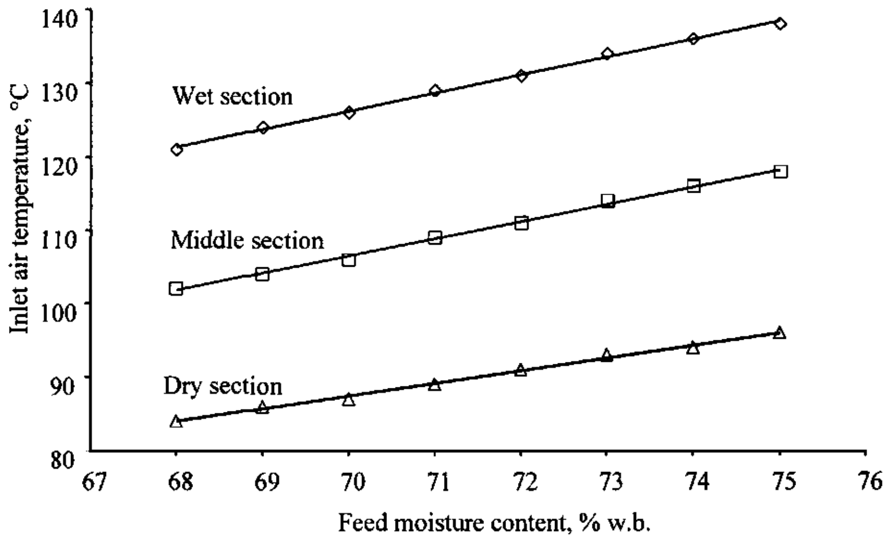

Fig. 9.4 Inlet air temperatures required to compensate for feed moisture changes

Moving away from feed moisture content to feed rate, a similar picture is seen in Fig. 9.5. However, here it can be seen that the slope of the lines is greater (the gains for all these determinations is shown in Table 9.2), and that the first and middle sections meet the maximum temperature with less than 5% increase in feed rate. The limit for the final section is slightly greater at 5%. Therefore varying the temperature to only a single section of the dryer cannot compensate for more than 5% increase in feed, but even by varying all three sections together the change in feed rate that can be compensated is less than 15%. This is quite a minor fluctuation in a manually fed factory, and could even be expected on a regular basis on a production line with automatic feed rate regulation.

With all three sections requiring increased temperature at the same time, there would be a fall in boiler pressure, reducing the maximum temperature attainable until stoking (normally with wood, manually) could compensate. This would add a further, unpredictable, delay into the control loop.

Table 9.2 Gains of various inputs for constant discharge moisture output

	Wet	Mid	Dry	Units
Change in air inlet temperature for a change in feed rate	2.6	2.6	2.1	°C per % of standard feed rate
Change in air inlet temperature for a change in feed moisture	2.4	2.4	2.4	°C per percentage point m.c. w.b.
Change in feed rate to compensate for a change in feed moisture content	-0.9			% of standard feed rate per percentage point m.c. w.b.

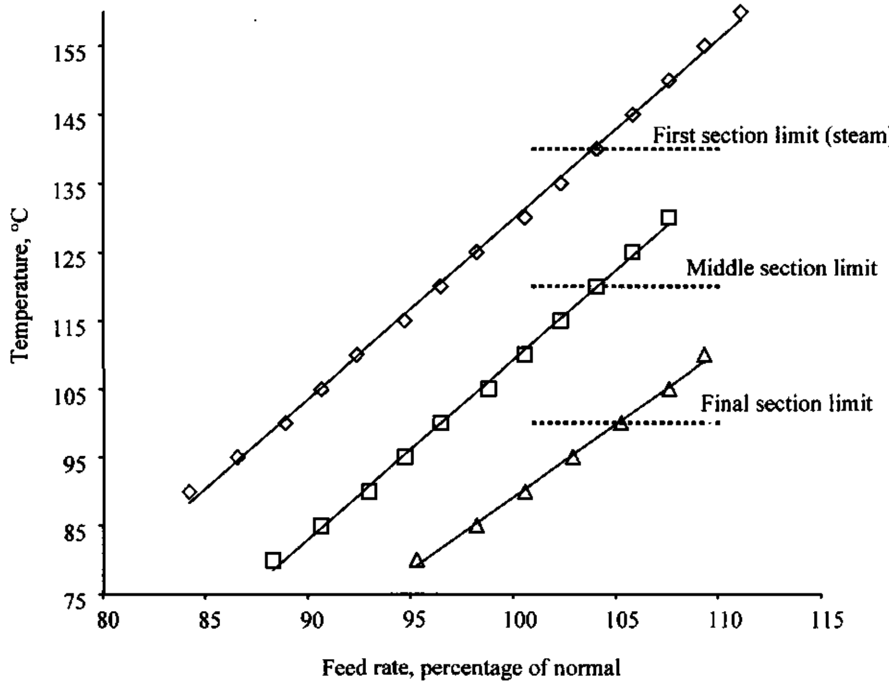

Fig. 9.5 Inlet air temperatures required to compensate for feed rate changes

To handle transients in feed rate, some further increases in temperature would be required to handle overshoots in discharge moisture content as the controller starts its action. It is clear that inlet temperature control alone is not effective at control of discharge moisture for a tea factory.

Other variables such as ambient dry bulb and wet bulb temperatures, and dhool temperature, were found to have only minor effects on the process, with much less impact than feed moisture content changes.

It is clear that feed rate must be controlled, as typical disturbances in the uncontrolled situation cannot be compensated for by control of the dryer air inlet temperatures. If good control of feed rate can be attained, this would allow the dryer and heating plant to be operated at maximum capacity, improving the factory economics.

If the dryer is to be operated at full capacity by feed rate management, then some modification of feed rate might be necessary for variations in feed moisture content. Figure 9.6 shows the relationship between feed moisture and feed rate. It is clear from this that the changes required are minor, and for control action to be taken, there must already be a precise feed rate control system. If control of feed rate is worse than ±1%, as is more than likely then feed moisture variation may be ignored.

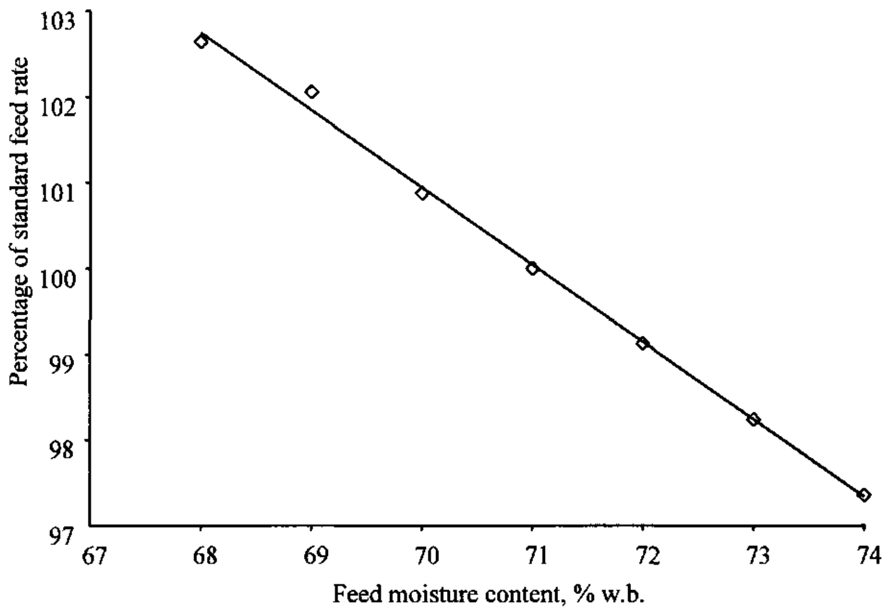

Fig. 9.6 Feed rate required to obtain 3% moisture at discharge with varying feed moisture content.

Accuracy of feed rate regulation to better than ±5% will be very difficult to maintain in practice. Existing types of feed measurement system are able to maintain consistent feeds to better than 10% deviation, but will need to be improved to ensure that there is less than 5% deviation. Feedback control is hardly practicable, as there is at least 45 minutes delay between material entering the continuous processing system and it reaching the dryer, and another 10 minutes before reaching the two thirds sensing position.

A further disturbance to the feed rate is the change in fermenting time. As the fermenter is speeded up or slowed down, there is a step change in feed rate for the duration of one conveyor length of discharge, with a constant feed rate, then the feed rate will revert to the original level. As the changes in feed rate due to this disturbance are likely to be greater than 10%, it is recommended that the changes are made frequently and in as small a step as possible. When determining the initial fermenting time, the initial value should be set higher rather than lower, so that any correction will result in over-dried tea rather than under-dried.

The dryer needs to be made less sensitive to feed rate fluctuations. In practice, with high weirs and the corresponding long residence times, coupled with the amount of back mixing occurring with the poor fluidization in deep beds, there will be a significant buffering effect reducing output fluctuations. However this is at the expense of quality, as not only will there be long residence times in the dryer, but also a very wide spread of particle residence times about the mean.

If the inlet temperature to the second stage of the dryer is controlled, and the first and last stages are at a fixed temperature, then energy may be saved by using a simple control system on the inlets to the first stage to keep the exhaust temperature of this stage below a nominal value, such at 90°C. This will have the effect of reducing the heat required to a minimum if there is an interruption to production, or during the startup phase, while allowing the normal inlet temperature to be used during normal production. On the last stage, at the discharge end of the dryer, the differential between inlet and exhaust temperatures is not enough to utilise such a control system; to maintain the correct inlet temperature with varying heat source performance, a thermostatic controller may be used sensing on either the inlet or, better, the exhaust.

9.5 Conclusions

A simulation model of a fluid bed dryer enables conclusions to be drawn rapidly on the operation and control of the dryer that would only be possible after a very long series of experiments, entailing the spoilage of large quantities of tea. It enables an understanding of the effects of various types of disturbance on the system and the operational characteristics of the dryer.

To maintain constant dryer discharge moisture, feed rate to the dryer should be controlled as accurately as possible, and at least to within 5% of the optimum. If moisture content varies, then feed rate may be modified slightly, as a feed forward controller, to take account of the new moisture content.

In a dryer using a boiler as the heat source, no thermostatic control is necessary unless there is spare boiler capacity; dryer control should be by correct sizing of the radiators.

In a direct fired system, where thermostatic controllers are required or already present, then at the wet (feed) end they should be used for on/off load sensing only. The middle section of the dryer should be controlled by feedback from the end of the section. The dry section of the dryer should also be controlled from the end of its section.

Control of dryer discharge moisture by modulation of air inlet temperature can only be achieved if the design of the dryer and its heating system allow adequate heating capacity. Before a control system is added to an existing installation, the availability of reserve heating capacity must be established.

9.6 References

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10 A comparison of dryer types used for tea drying*

10.1 Abstract

Simulation models for various types of tea dryers were constructed from a thin-layer drying model and used to determine how these types of dryers would perform with different levels of inputs. Three dryer types were commonly found in practice, two others are not generally used and one type is unknown in practice. The information gained from the simulations could show which type of dryer was more efficient at heat and air utilisation. Graphs of the moisture content of the product discharged from the dryer show which variables need to be controlled most tightly in practice, and which variables might be successfully manipulated by a control system. This study has implications not only for the control of various dryer types, but for the physical design of the dryers. The multi-stage fluid bed dryer with re-circulation is found to have the best combination of characteristics, and is the type increasingly used in industry.

10.2 Introduction

In the tea industry several type of dryers are used to reduce the moisture content of the wet fermented dhool from about 70% w.b. to 3% before packing. The most frequently applied dryer is the fluid-bed dryer followed by the Endless-Chain-Pressure (ECP) dryer. The hot feed ECP, although it has advantages and was widely advertised, is rarely encountered and a cross-flow conveyer dryer is not normally used. As each tea factory will normally have only one, or at most two types, a direct comparison of performance is difficult. Simulation models can be used to compare the equipment and to reveal their specific operation characteristics. The results of such comparison can be used in ranking dryer types for investment decisions.

Previous studies by Temple and van Boxtel (1999a) have validated a simulation model of the fluid bed dryer, and shown this type to be highly sensitive to load variations. Possibly some other configurations of dryer used in the tea industry might be less sensitive to changes in feed rate, and thereby more stable in operation. Alternatively, a dryer that is more sensitive to feed rate fluctuations might also be more sensitive to changes in hot air temperature and flow rate. It would therefore be more susceptible to a control system, as relatively small changes in the manipulated variables would have more effect on the process.

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The fluid bed dryer model used in the previous work can be re-configured to simulate the behaviour of other types of dryer (ECP, hot-feed-ECP and conveyor dryer). The predictions for each dryer type can then be compared to make an assessment of suitability for application of a control system.

The variables to be investigated should be the effect of feed rate, inlet air temperature, inlet air flow and product residence time on dryer performance. Performance is measured as the moisture content of the dry tea discharged. Conveyor-type dryers have an additional variable that can be manipulated: the residence time, which is a variable that is mechanically varied directly. For the fluid bed dryer the weir height is set and not varied during operation, and residence time is some function of the weir height.

Table 10.1 Common operating conditions.

Altitude	650	m.a.s.l.
Ambient dry bulb	22	°C
Ambient wet bulb	18	°C
Dhool temperature	19	°C
Feed moisture content	71	% w.b.
Inlet temperature	100	°C
Fluid bed air velocity	1.0	m/s
ECP, cross flow air velocity	0.56	m/s
ECP area per layer	8.55	m^2
ECP residence time	15	minutes
Fluid Bed Weir height	50	mm
Fluid Bed area per section	0.72	m^2

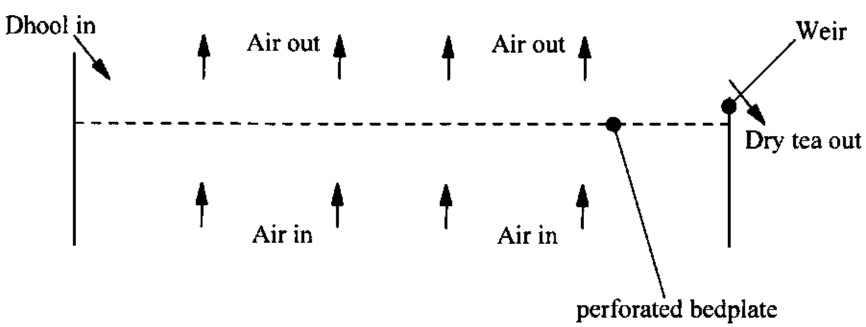

Fig. 10.1 Single stage fluid bed dryer schematic diagram

10.3 Dryer types.

Four types of dryer were modelled. The fluid bed dryer (Fig. 10.1) was a basic single stage unit, with a uniform inlet air temperature and flow rate along the whole bed. A single variable weir was used. Because the total mass at each position in a fluidized bed is constant, the speed of movement of dry mass (tea) decreases along the bed as the tea dries and the mass of water reduces.

An alternative to this would be a cross flow dryer (Fig. 10.2), superficially very similar, but without a weir. The bed is moved mechanically at a constant speed, and the air velocity is in the region of 50% of that in the fluidized bed dryer, so the tea remains static on the bedplate. In a practical dryer of this type, agitation or mixing of the bed would have to be provided at intervals to avoid the formation of a drying front, with over-dried tea at the bottom of the bed and very wet tea at the top.

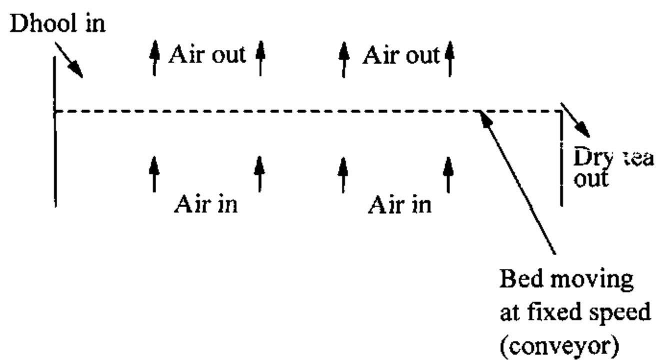

Fig. 10.2 Schematic diagram of cross-flow conveyor tea dryer.

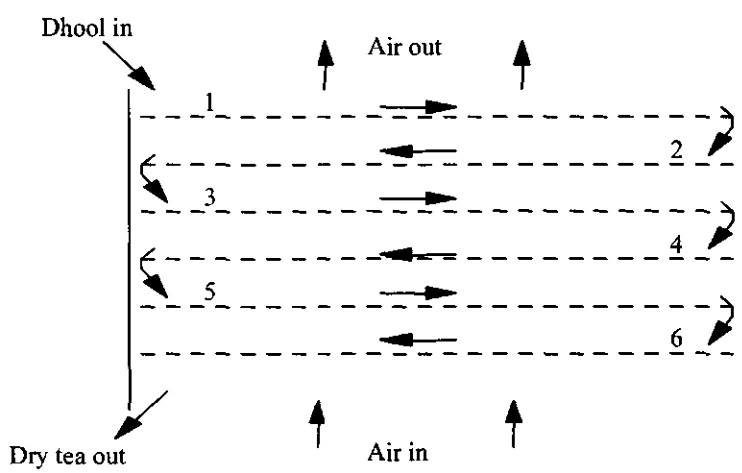

Fig. 10.3 Schematic diagram of ECP dryer.

The ECP or Endless Chain Pressure dryer was widely used before the fluid bed dryer became popular in the tea industry. It is a conveyor-type dryer, and addressed the problem of mixing the bed by dropping the tea from one conveyor to the next one below it (Fig. 10.3). As in the conveyor dryer, the air velocity is in the region of half that required for fluidization, and the tea is moved through the machine at a constant rate by the mechanical action of the conveyors (not illustrated in detail here). To avoid the wastage of the hot air exhausted from the dry end of a cross flow-dryer, the ECP type uses the exhaust air from the last section (i.e. the bottom chain) as the inlet to the previous section, and so on, ensuring that all the exhaust air is saturated. It is a hybrid between a countercurrent flow and a cross flow type. Commercial types of dryer have four or six stages.

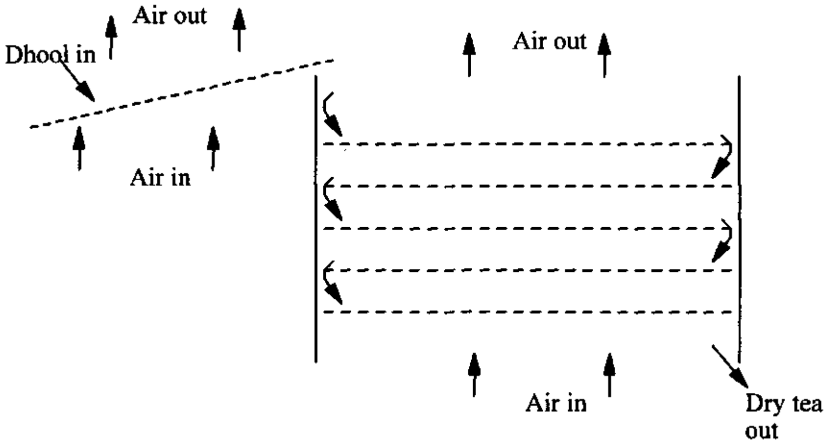

Fig. 10.4 Schematic diagram of ECP dryer with Hot Feed.

The problem with the ECP dryer is that the drying rate in the first stage (where the product is just introduced in the dryer) is very low, as the air going into it is almost saturated. The tea is heated up without being dried significantly, and this adversely affects quality. In an attempt to overcome this problem, a modification was marketed, known as a "Hot Feed". The conveyor feeding the dryer was supplied with air of similar temperature and flow rate to the main dryer. This enabled the initial drying to be very much more rapid, without loosing much efficiency, as both the air from the main dryer and the hot feed would be at, or close to, saturation. For comparability with the ECP dryer modelled in this study, the model of the Hot Feed dryer used the top section of the ECP for the hot feed, leaving only five sections in the main ECP dryer (Fig. 10.4). This dryer appears to have many advantages; there is the rapid initial drying as is seen in the fluid bed dryer, combined with the increased efficiency found in the ECP type. Unfortunately few if any of this type of dryer are found in practice now.

The air model for all the dryers was similar, where necessary using the exhaust characteristics from one stage as the input to the next stage. The model for the material being dried in the cross flow, ECP and Hot Feed type could be considerably simplified from the fluid bed dryer, with the dry matter flow rate through the dryer being constant.

The fluid bed dryer model consisted of nine similar, well-mixed, subsections in series, to simulate the plug-flow with back mixing found in such a dryer. For the ECP dryer, each section was split into eight subsections, giving a total of 48 subsections. Within each subsection, the dhool was assumed to be well mixed, but there was pure plug flow from one subsection to the next. This models the conveyor dryer nature of the process, with a small amount of mixing as the dhool falls from one section to the next. The air from all the subsections of one section was mixed before being fed to the next section.

In the hot feed dryer, the total number of sections and subsections was the same, but the first section to receive dhool had its own air supply, so for the same size of dryer the air volume requirements were double.

The cross flow conveyer dryer had the same number of subsections, 48, but instead of the exhaust air from one layer being the inlet for the one above, each was supplied with inlet air as in the fluidized bed dryer.

Because these dryers have different operation characteristics, for a valid basis for comparison, the same air inlet temperature should be used for all dryers. For the fluid bed dryer, a single inlet temperature and a single (average) air velocity should be used.

It was not possible to ensure direct comparisons between dryers by using the same total bed area, or the same total air supply, as the use factors of each were different in each type. Instead, the same air inlet conditions of temperature and flow velocity were maintained for the non- fluidized types, and a constant but higher velocity at the same temperature was used in the fluid bed dryer. Feed rates were determined which provided 3.0% moisture content w.b. at the discharge for each type, then the results were scaled to compare a similar percentage change in airflow or feed rate. Absolute residence times and temperatures were compared.

10.4 Results and discussion.

The drying rate efficiency factor of 0.6 which was found necessary for the fluid bed dryer simulation was also used for the other types. It could not be validated in practice, but any inaccuracies would lead only to errors of scaling of the dryer; the operating characteristics would not be affected. The results for the ECP type were similar to performance levels found in practice.

Some fluid bed dryers are operated with a single inlet air supply. Alternatively separate air inlets are used with a high temperature in the first stage for rapid drying (up to 140°C), lower in the middle (110°C) and a temperature unlikely to damage the tea at the end (90°). In many dryers the energy utilisation is improved by feeding the exhaust air from the dry end to heaters for the middle and wet end. Simulations were performed on all three types of fluid bed dryer, but graphical comparisons with other types only used the first type.

Table 10.2 Comparison of energy use of six types of dryer.

Type:	Fluid bed	Fluid bed three stage	Fluid bed recirculating	Cross flow	ECP	Hot feed
Energy use (MJ/kg)	2.80	2.84	2.30	2.95	2.11	2.18
Compared to FBD	100%	102%	82%	105%	76%	78%

The heat utilisation for each type of dryer was calculated when they were all discharging tea at 3% moisture. The results were calculated in Table 10.2 as MJ/kg of wet dhool (71% m.c. w.b.). As the ratio of dry matter and moisture are identical in each dryer model, the ratio of energy use may also be considered in terms of energy per unit of moisture evaporated.

The sensitivity of the dryers to variations in feed rate was determined by altering the simulated feed rate either side of that which gave 3% moisture discharge. As the feed rates for each model are different, the results are expressed in Fig. 10.5 as percentage of feed rate giving 3%, so each type of dryer can be compared directly.

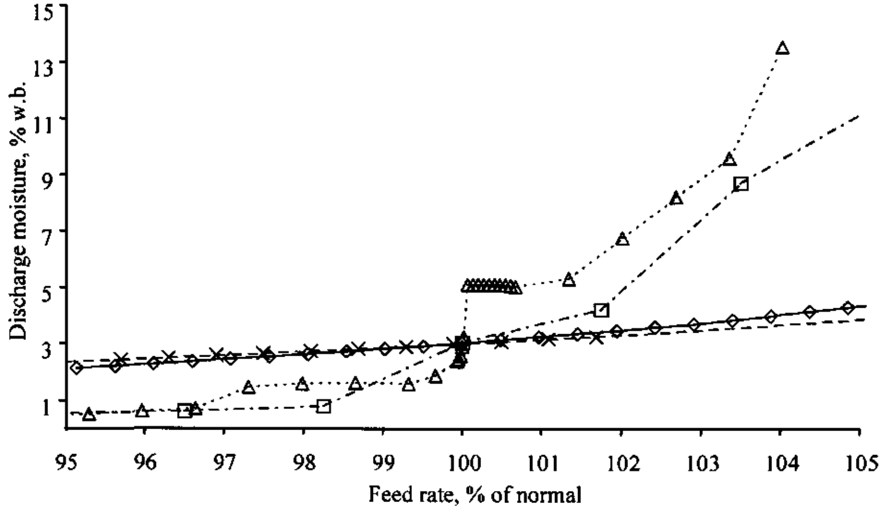

Fig. 10.5 Discharge moisture response of four dryer types to different feed rates. ***◊ FBD; × Cross flow; Δ ECP; □ Hot feed.***

The cross-flow conveyor dryer is the least sensitive to different loads and is closely followed by the fluid bed dryer. The ECP and Hot feed types are most sensitive, reacting with a form of staircase response (additional simulations were carried out in the region of the anomalies). No physical explanation can be suggested for this effect.

It appears that it is extremely difficult to maintain the performance of any type of tea dryer in the face of fluctuating feed rate; the reason for this is the extreme range over which drying is performed. The starting water per kilogram of dry matter is eighty times the final water content, so unless there is some intrinsic design feature acting to stabilise performance, then feed rate must be controlled extremely accurately. The more efficient the dryer, the less spare capacity there is to take out fluctuations; the data from Table 10.2 bear this out.

As the simulations were carried out with standard performance obtained at an inlet temperature of 100°C, the response of the different types to changes in inlet temperature may be compared directly (Fig. 10.6).

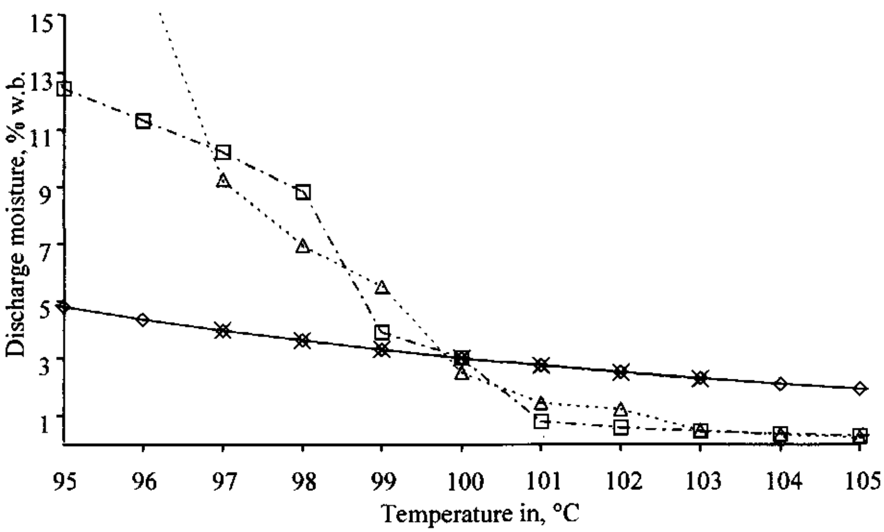

Fig. 10.6 Moisture discharge performance of four types of dryer at various inlet temperatures. ***◊ FBD; × Cross flow; Δ ECP; □ Hot feed.***

Here the fluid bed and cross-flow types have almost identical performance; the hot feed and ECP types have a much steeper curve, both types being similar. The steeper response of the ECP type is an advantage, in that temperature controls may be able to correct for fluctuations in feed rate with smaller temperature differentials. However the steeper response to feed rate changes may negate this effect.

To compare fluctuations in airflow rates, the values have to be plotted as a percentage of the standard setting, as the fluid bed dryer has approximately double the superficial velocity of the other types. In terms of air use per kilogram of dhool dried from 72% to 3%, Table 10.3 shows that the fluid bed and cross flow dryers use the most air per kilogram of tea dried. This has implications for electrical power consumption, powering the fans to deliver the air.

Table 10.3 Comparison of air utilisation for six types of dryer.

Type:	Fluid bed	Fluid bed 3 stage	Fluid bed recirculating	Cross flow	ECP	Hot feed
Air use (m^3/kg)	41.9	37.2	41.8	43.1	31.7	32.6
Compared to FBD	100%	89%	99%	103%	76%	78%

The graph resulting from these simulations (Fig. 10.7) shows almost a mirror image of Fig. 10.5. The ECP and Hot feed types have a very steep response, but the fluid bed and cross flow types show much less response to change in air flow. The step-wise response indicates the need for tight air flow-rate control and that small variations in air flow rate might disturb the final moisture content significantly.

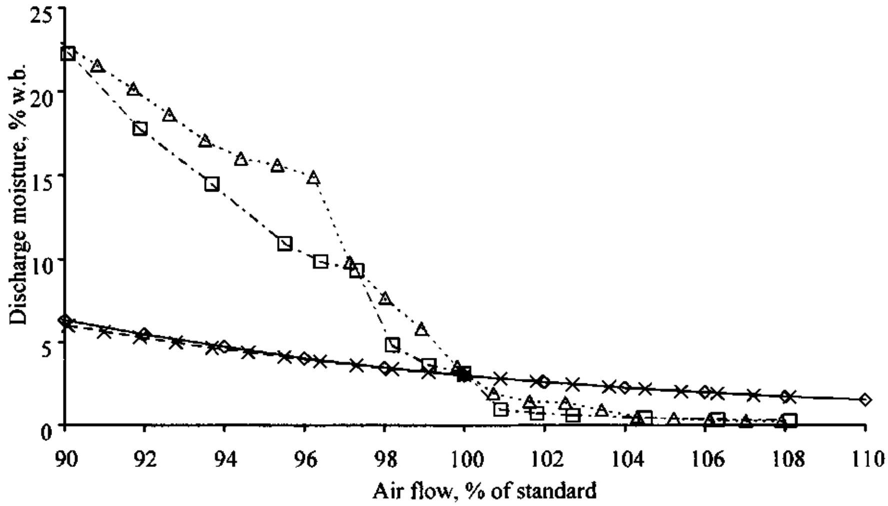

Fig. 10.7 Discharge moisture response of four dryer types at varying superficial air velocities. ***◊ FBD; × Cross flow; Δ ECP; □ Hot feed.***

For the fluid bed type, it has already been shown that the air velocity must be maintained within a narrow range to maintain fluidization (Temple and van Boxtel 1999b). For the other types, an air velocity which approaches that of the fluid bed dryer must be avoided, as there is usually no provision for handling any material that might be eluted at higher velocities. Apart from this, there is no restriction on the air velocities which might be employed, so this might be a suitable variable to be manipulated by a control system.

For most air heaters, any change in airflow will affect the temperature of the air. Some heaters may have a constant power output, others might have a more complex relationship with airflow so any use of air velocity as a manipulated variable will have to take into account the response of the heater system also. In this case the heater is modelled by a first order process (time constant 300 s) with delay (10 s).

In a fluid bed dryer, the residence time is controlled by the weir height, and cannot be measured directly as it depends on the moisture profile in the bed. In this case, the residence time is determined by dividing the total dry matter on the dryer bed by the feed (or discharge) rate of dry matter, assuming a steady state. In the other types, the residence time is determined mechanically by the conveyor mechanism, and is often varied to control drying.

To simulate the effect of changing residence time, the weir height of the fluid bed dryer was changed either side of the standard setting; in the other types, it was varied directly. The residence times of the other dryers was set at 15 minutes or 900 seconds, a typical value found in practice with an ECP type of dryer. With the dryer settings used in the fluid bed dryer, the standard weir height of 50 mm gave a residence time of 897 seconds, which is surprisingly close to the other types considering the completely different flow pattern in the different dryers. This coincidence was fortunate for the comparison. The curves shown (Fig. 10.8) are remarkably similar, apart from the steps shown by the ECP and hot feed types.

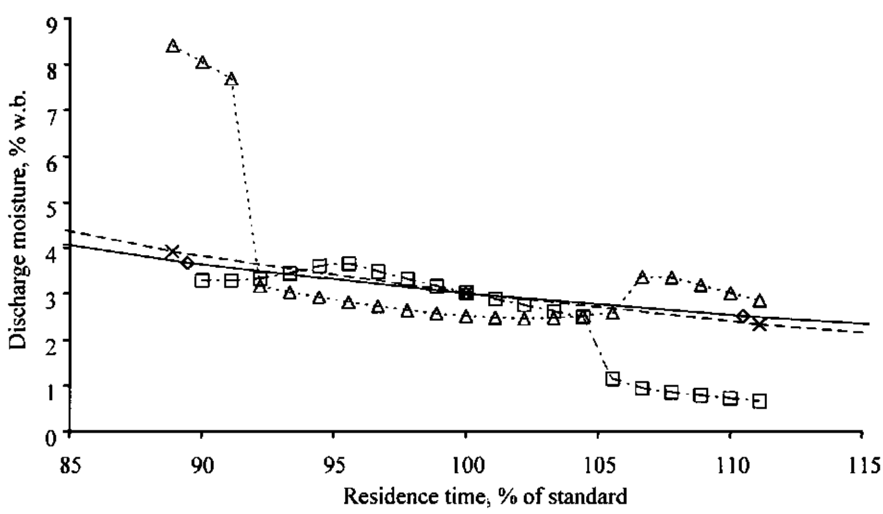

Fig. 10.8 Discharge moisture performance of four dryer types at varying residence times. ***◊ FBD; × Cross flow; Δ ECP; □ Hot feed.***

Such steps are a feature of these dryer types in all the performance graphs; because of the downward and cross flow of the dhool and the upward flow of the air, the interactions are not easy to analyse, and are beyond the scope of this paper.

A further step towards understanding the performance is the dynamics of each system. The previous data were all obtained by setting the required conditions in the model then waiting until a steady state was reached. It is important to know how the system responds to change, to ensure stability in a control system. Three parameters are important, and can be used to determine initial controller values by the Cohen and Coon method if the process approximates first order behaviour. They are: the delay time, t_d, between the change in input and the first change in output, the system time constant τ, which is a measure of how rapidly the system starts changing, and the static gain K. The gain is the ratio between change in output and the change in input causing the change. The outputs are in terms of moisture content, so are independent of the dryer size, but the feed rate for each dryer being simulated is different; the inputs are therefore represented as the size of the change in feed rate as a proportion of the initial value to enable a comparison of the dryer types.

Each system was disturbed from normal operating conditions by a 5% step increase in feed rate, and the response in terms of discharge moisture content was analysed. To compare the response using different feed rates for the different dryer types, the change in moisture content of discharge is shown, normally starting at 3%. Because the 3% discharge of the ECP dryer occurred at an anomalous part of the curve, during a rapidly changing part of the staircase characteristic, the response at a slightly lower value is shown.

Table 10.4 Process reaction curve characteristics for different dryer types subjected to a 5% step increase in feed rate.

	Fluid Bed	**Fluid bed 3 stage**	**Fluid bed re-circulating**	**Cross-flow**	**ECP**	**Hot feed**
t_d	17	17	17	680	680	680
τ	400	450	600	350	n/a	n/a
mc % increase	1.31	1.49	1.94	0.79	8	10.5

It is clear from Table 10.4 that the initial delay t_d is very much shorter for the fluid bed dryers than all the other types. In this type of dryer, any change in performance is transmitted through the bed quickly, as the moisture content profile is disturbed, and there is a proportion of forward mixing of the material. In contrast, the delay times of the conveyor transport types are very much greater, as until a substantial proportion of the bed is filled with material at the new feed rate, no difference in performance will be detectable. The smaller the value for t_d and τ the easier it is to control a system.

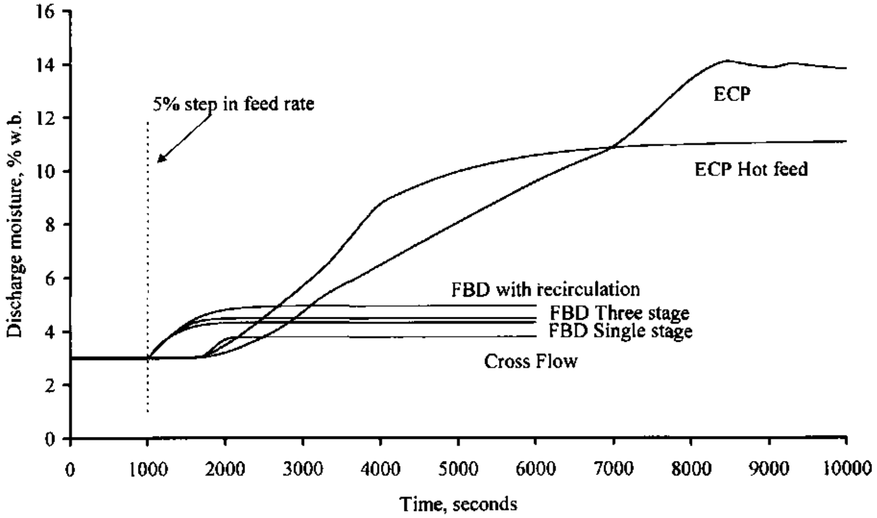

Fig. 10.9 Discharge moisture response of different dryer types to a 5% step increase in feed rate at 1000 seconds

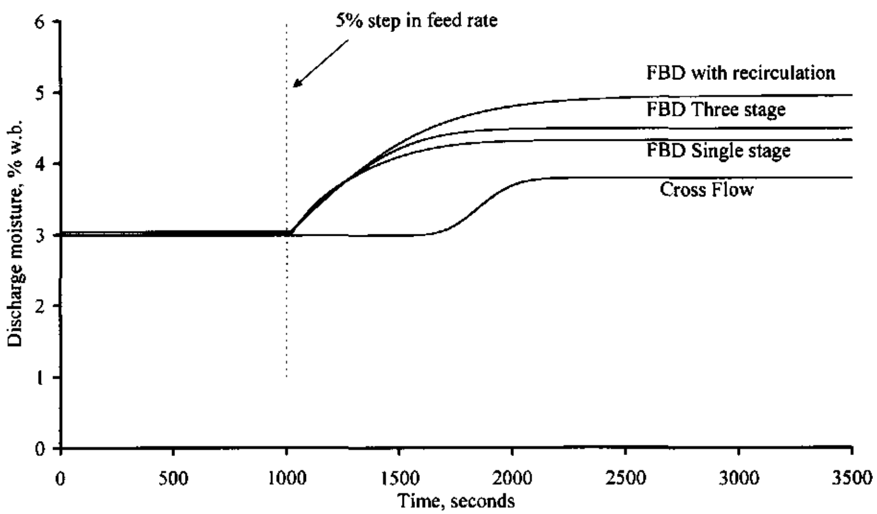

Fig. 10.10 Discharge moisture response of fluid bed and cross flow dryers to a 5% step increase in feed rate at 1000 seconds (detail of Fig. 10.9)

It was not considered valid to quote a figure for the ECP and Hot Feed dryer response time τ, as the response was not a sigmoidal curve. The process reaction curves for all types are shown in Fig. 10.9. The responses are clearly much slower, and the non-sigmoidal character indicates that the design of a control system might be very much more complex than for the fluid bed or cross flow dryers.

To see the response of the fluid bed and cross flow dryers more clearly, these are shown on an expanded scale in Fig. 10.10. For the fluid bed types, the response becomes slower and more extreme as multi-staging and re-circulation increase the efficiency. The cross-flow type, with fixed transit times, has a long initial delay followed by a small, reasonably rapid transient. The control of this type of dryer would be relatively simple, if adequate compensation for the effects of the delay is made.

The value of static gain K is not reliable for the ECP and Hot Feed types, as the static curves (Fig. 10.5) showed the response was not simple and contained some steps. The gain will be determined by how close to a step the system was before the change in input, and whether the change covered this region. This is likely to make controller design very difficult.

10.5 Conclusion

Modelling and simulation of different types of dryer can yield very useful information on the characteristics of the different systems. The efficiency of utilisation of heat energy, and the amount of electrical energy required (for air movement) can be estimated from the simulations and be used for ranking equipment.

The relationships revealed by the simulations show how each type of dryer might respond to changes in operating conditions, and can give guidance to operators as to which are the most critical variables to manage during operation. These results are summarised in Table 10.5.

Table 10.5 Ranking of dryer types (1 is best, 6 is worst, = indicates values of equal merit).

	Fluid Bed	**Fluid bed 3 stage**	**Fluid bed re-circulating**	**Cross -flow**	**ECP**	**Hot feed**
Heat utilisation	4	5	3	6	1	2
Air utilisation (electrical energy)*	5	3	4*	6	1	2
Speed of response to change	1	2	3	4	5	6
Speed of initial drying	1=	1=	1=	1=	6	1=
Stability with temperature change	1=	1=	1=	1=	5=	5=
Stability with feed rate changes	2	3	4	1	5	6

*Electrical energy required for recirculation not included.

It can be seen that the more efficiently a resource (heat, or drying capacity of the air) is utilised, the more severe are the consequences of overloading or underloading, with implications for the design of the different dryer types

Although the moisture content of the product of the ECP type dryer changes more dramatically with feed rate changes than the fluid bed dryer, the response to changes in temperature and airflow are more substantial also. As both of these can be varied, as opposed to only temperature on the fluid bed dryer, it seems as though the ECP would be more easily controlled. However, the strange steps in the characteristic curves for this type of dryer warn of potential instabilities that might affect a controller and will complicate the controller design for the ECP and hot feed type of dryer.

The best combination of dryer characteristics indicated by this study is found in the multi-stage fluid bed dryer with re-circulation; it is interesting to note that this type of dryer is increasingly being adopted by the tea industry.

The procedure shows how modelling can be used to discover the performance characteristics of a dryer, and to compare different configurations without building them. Although the models of those not found in practice were not validated, the characteristics are likely to be modelled well enough to enable selection of an operating principle. They may also be used to estimate how stable such a machine might be, and how amenable (or necessary) a control system would be for consistent operation. Apart from the performance characteristics considered in this paper, many more factors must be considered when selecting an item of equipment, including the first cost of the equipment, maintenance costs, reliability and complexity of operation.

10.6 References

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10.7 Acknowledgements

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11 Overall Conclusion

The objective of this work was to determine the potential for control systems on fluidized bed tea dryers. As very little relevant published data could be identified on the drying of tea, it was first necessary to investigate in some detail the drying process for tea particles. Then it would be possible to use these data to construct a mathematical model of the drying process and a simulation model of a fluidized bed dryer. Once validated, the simulation model could be used for studies of possible control systems, as well as other investigations.

The equilibrium moisture relations, fluidization characteristics and drying dynamics of tea particles have been established by experimental studies, adding to the very sparse literature on the subject. Unexpectedly, the drying rate in a thin layer was found to depend strongly on the superficial velocity of the drying air. Although this effect was not found in thin layer drying studies of other products, the characteristics of the material being dried could explain the behaviour. Other experimental work established some temperature constraints on the drying process in order not to compromise the quality of the finished product.

The next step was to develop a mathematical model of the drying process using the drying characteristics of tea in a fluidized bed, as determined by this study. From this set of equations, a simulation model of the process was produced using a computer simulation package. This model was validated against an experimental batch dryer, a pilot scale and a full-scale commercial fluid bed dryer and was found to represent the practical dryer accurately once a single calibration factor had been added. This factor had the same value for all fluid bed dryers tested. Following validation of the model this allowed the control of the dryer to be studied with some confidence, although practical measurement limitations restricted the validation to the steady state situation.

The fluidized bed model had to take into account the uncontrolled movement of material along the bed, maintaining a constant bed loading as moisture evaporated. To change from a fluid bed model to a dryer type where through flow is determined by a conveyor mechanism, the model was simplified. A drum dryer as used in green tea would be somewhere between the fluid bed model and the conveyor model. The exhaust properties of the air were determined in such a way that the exhaust air could be recycled in the model, as sometimes happens in practice. Some types of dryer used in the tea industry were evaluated using the model, including the options for recirculation of exhaust air.

The simulation model demonstrated that feedback control of the dryer was possible. Using the objective measurement, tea moisture, as the feedback element provided a good degree of control once compensation had been made for the extensive time delays inherent in the system. Unfortunately in practice, measuring discharge moisture is expensive and not particularly reliable. In order to utilise a low cost, simple and reliable temperature measurement instead of the moisture measurement, an inferential controller was designed, and found to give good performance in the model. It was found that a considerable simplification to the inferential estimator calculations could be made without compromising the system performance. This would allow implementation of the controller on simpler, lower cost hardware.

Investigations revealed that although the controller tuning values supplied by the standard methods of Cohen and Coon, and Ziegler-Nichols were adequate at the standard operating conditions studied, once the extremes of the operating range were reached the system could become unstable. An alternative, model-based, tuning system was developed which mapped phase margin, gain margin and integral squared error on axes of controller gain K_c and integral time τ, allowing the identification with settings allowing acceptable margins with minimal integral squared error values.

The practical limitations on heat supply in a commercial tea factory mean that a dryer is normally operated close to its maximum capacity, leaving little or no spare capacity for dealing with disturbances in the feed rate or feed moisture. Thus any control system is relegated to the role of reducing the heat requirement when the dryer is at part load.

The simulation model clearly indicates that the disturbance with the greatest impact on dryer performance is the feed rate, so in the absence of spare heating capacity, the delivery of feed material to the dryer must be controlled accurately.

A further use of the simulation model is to compare various types of dryer, including possible types that have not yet been built or tested on tea. A comparison of types indicates that the fluid bed dryer can be almost as efficient as the most heat efficient type, the ECP dryer, if recycling of dry exhaust air is employed. It will always require more electrical power for air movement than other dryer types, especially if air recycling is required. The fluid bed dryer is less sensitive to disturbances than the ECP and related dryer types, and shows a more rapid response to fluctuations in load, making it potentially easier to control.

The major benefit of the fluid bed type is that it can go through the initial stages of drying very quickly, thus arresting the fermentation process and improving quality. As moisture evaporates, the speed of the material along the bed reduces together with the rate of drying, allowing the tea more time to dry when the rate is least. This study has shown that the optimum fluidization conditions are met with a discharge weir of 50 mm or less, while in practice higher weirs are often used.

The fluid bed dryer is therefore the best choice for drying of macerated tea particles, in all respects apart from electrical power consumption. Unfortunately, the cost of electrical power, both in capital and running costs, is a major contributor to the cost of operating a tea factory. However, in balance, the fluid bed dryer can still be considered the best technology available at present.

When choosing a dryer for macerated teas, the choice should be a fluid bed dryer, with close control of feed to the processing line, and feedback control of the inlet temperature to the centre section of the dryer to handle other fluctuations. The weir height should be fixed at 50 mm high, giving the optimum conditions for fluidization, a short residence time and good drying efficiency. If a gasifier is chosen as the heat source, rather than a steam boiler system, then there could be adequate capacity for a feedback control system to handle fluctuations in feed rate. The sensor for the feedback control should measure the exhaust temperature about two-thirds of the way along the bed.

The model developed in this study can be utilised in the design of new fluid bed dryers, to establish the requirements for a given feed moisture content and feed rate. It can also be used to determine operating conditions and to design a controller.

The combination of experimental work to establish the drying characteristics of a material, followed by mathematical and simulation modelling, was found to be an extremely powerful technique for understanding and design of dryers.

This work has demonstrated that control of fluidized bed tea drying is possible, and that an inferential controller will allow the use of low-cost instrumentation. Practical limitations of many present dryer installations restrict the application of controllers, but in factories where sufficient reserve heating capacity is available, immediate application is possible.

12 Appendix –The physical properties of tea

12.1 Introduction

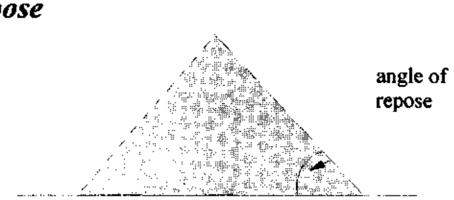
Before designing any equipment for drying or handling tea, certain physical properties must be measured. Hongfan Yin (1985) reports measurements made on various types of green and black tea, including black broken tea which is of relevance to this work. Chen Jiazhen and Lin Weijian (1986) report on the frictional properties of broken black tea, and quote a value of coefficient of broken black tea on metal between 0.22 and 0.35. They state that the internal friction coefficient is greater than that relative to engineering materials. It increased with increasing moisture content and reducing particle size. No other values relevant to black tea could be found.

Table 12.1 Physical properties of tea reported by Hongfan Yin

Property	Material condition	Value
Particle density	7% m.c. w.b.	1380 kg/m^3
Bulk density	8.3% m.c. w.b.	367 kg/m^3
Thermal conductivity	8.3% m.c. w.b.	0.0483 W/m.K
Specific heat	6.5% m.c. w.b.	1.63 kJ/kg.K
Thermal diffusivity	8 % m.c. w.b.	8.34 e^{-8} m^2/s

In order to study fluidization of tea, its flow properties must be understood. In particular, dhool exhibits some strange properties when damp and containing a proportion of tea fibre, which inhibits fluidization at the start of drying. If proper fluidization is not achieved in the initial drying stages, when the hottest air is used, then balls of tea are formed which dry on the outside ("case harden"), and will not dry out properly inside. An understanding of the angle of repose and fluidization properties is necessary for the design of dryers, and for any other equipment handling tea.

12.2 Angle of repose



The angle of repose is defined by Henderson & Perry (1981) (p 41) thus "When a granular material is permitted to flow from a point into a pile ..... the shape of the pile is characteristic of the material. The angle which the side of the pile makes with the horizontal is called the angle of repose. For any material, it varies with the moisture content and amount of foreign material present, increasing with an increase in either.

The tangent of this angle is recognized as the coefficient of friction of the material on itself."

12.2.1 Method of measurement

A sample of the dhool or tea to be tested is poured through an opening less than 1/4 of the diameter of the final heap, to achieve a point. A light rigid plate (of thin plastic material) is rested against the edge of the heap to give a distinct edge against which to measure. A protractor is used to measure the angle between this plate and the horizontal surface on which the heap has been made. The measurements are repeated on different heaps made with different samples of the same material and repeated on the same samples rebulked and resampled.

12.2.2 Measurements

Table 12.2 Effect of moisture content on angle of repose

Sample	moisture % w.b.	angle of repose
Fresh wet dhool	70	40
Dhool slightly dried	63	40
Dryer mouth	9	40

The measurements shown in Table 12.2 were not able to demonstrate a measurable difference in angle of repose between different moisture content of samples (despite the predictions of Henderson & Perry), yet they clearly behaved very differently when fluidization was attempted. A different method of measurement is needed to detect this. If the material is to fluidize well, then as tea is fluidized from the edge the heap must slump to retain the angle of repose. The new method can be termed the "Angle of Repose by Excavation". Following the determination of angle of repose in the conventional way, use a spatula, ruler or similar tool to excavate from one edge of the heap. Then determine the angle of repose of the heap on the side where the excavation has been carried out. The angle measured should be the greatest achievable before slumping occurs. The measurements using both techniques are shown in Table 12.3.

The differences are now beginning to show up. The pure fibre from the dryer hood contains all the longest fibre from the dhool, and these fibres inter-tangle to such an extent that a considerable overhang can be created. The fresh dhool does not contain anywhere near so much fibre, but the angle of repose by excavation can still be greater than 80 degrees. In a way, moisture will reduce the effect of fibre by softening the fibre.

Table 12.3 Comparison of methods of determining angle of repose on various grades of tea.

Sample or made tea grade	moisture % w.b.	Angle of repose	Angle of repose by excavation
Dhool ex fluidization test	63	40	40
Dryer mouth, additional material not used for fluidization test	9	40	40
Wet dhool fresh from line 2	70 +	40	80+
Dust 2 on factory floor	dry	43	43
Fibre ex dryer hood on factory floor	dry	90+	overhangs
Dhool cut at 2pm LTP, measured 2pm	70	40	90
Dhool cut at 2pm LTP, measured 3pm	70	47	90
Dhool cut at 2pm CTC, measured 2pm	73	40	90
Dhool cut at 2pm CTC, measured 3pm	73	47	90
PF1 being packed	3.3	36	36
PD being packed	dry	34	34
PF1 being packed	5.8	36	36

12.3 Particle size analysis

Table 12.4 Sieve analysis of dryer mouth made tea sample. Sample size = 200 g, Duration =15 minutes, amplitude = 6

Retained over screen (mm)	1.4	0.85	0.6	0.5	0.425	<0.425	Total
Weight retained	19	94.5	62	14	6.5	4	200
% retained	9.5	47.25	31	7	3.25	2	
Mean size d_p (assume largest <2.0 mm)	1.7	1.125	0.725	0.55	0.462	0.212	
$(x/d_p)_I$	0.055	0.42	0.427	0.127	0.07	0.094	
Mean diameter (mm)							1.195

12.4 Fibre

The fibre which is eluted from the dryer, particularly at the wet end, has a significant length which causes entangled mats to form. Sieve analysis is totally inappropriate for this material, and the best that can be done is to take a small sample and measure with a ruler. From initial measurements, the maximum length found is 45 mm, with width ranging from 1 mm down to less than 0.5 mm.

An important parameter for fibre is the entrainment velocity, the airspeed at which it is caught up in the flow and eluted from the bed. This was measured on the same apparatus as minimum fluidization velocity, and it was found that the majority of material is eluted at 1.0 m/s and 100% at 1.5 m/s. Therefore a very large proportion is going to be entrained at a lower velocity than minimum fluidizing (as found in ECP dryers) so any FBD must be designed to handle the fibre in a controlled way.

12.5 Geldart Classification of bed materials.

Particles in a fluidized bed can be classified as to their likely behaviour on the basis of mean particle size and density.

From preliminary measurements, the bulk densities of dhool and made tea are remarkably similar, when loose packed into a measuring cylinder. Measurements taken on dhool at 68% moisture wet basis gave 370 g/l and on dryer mouth tea at 2% moisture 340 g/l. This puts both dhool and made tea in the Geldart A group, which is described by Kunii & Levenspiel (1991) as "These solids fluidize easily, with smooth fluidization at low gas velocities and controlled bubbling with small bubbles at higher gas velocities."

The behaviour of wet dhool containing long staple fibre, however, tends more to a Geldart C type, with channelling being the precursor to turbulent/churning fluidization. This is supported in the observations on "Angle of Repose by Excavation" for fresh dhool. The angle of 80° determined by excavation (Table 12.2) demonstrates that the material does not flow easily, and will tend to clump together.

12.6 References

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13 Appendix – Rapid methods for moisture measurement in tea

13.1 Introduction

Before any drying research can proceed, fast and accurate methods of moisture measurement must be available, as well as for quality control in commercial factories. The official method for tea (International Standards Organisation 1980) does not actually measure moisture but loss in mass, as some volatile material is lost before all water is lost. It is an oven method, and requires drying until no more loss in weight is discernible; the period required for this is normally at least 8 hours at 105°C, so the usual technique is to place the sample in the oven overnight. The method has the advantage that many samples can be analysed at the same time, but the delay in getting an answer makes drying research (which might need the starting moisture content to find out the endpoint of an experiment) very difficult. An acceptable method for research purposes should give values to ± 0.25 percentage points of moisture content for dry tea (i.e. tea at 3% could return a value between 2.75% and 3.25%), or one percentage point for dhools. Commercially the acceptable error could be double that used for research.

Many of the methods used for grain or similar moisture measurement are not suitable for tea, particularly those based on conductivity. When measuring in the region of 70% wet basis, conductivity detectors are saturated; at the dry end of the range the variable particle size and variable proportion of fibre in dryer mouth samples makes calibrations unreliable. Some tea companies have tried and abandoned such instruments.

Although not instantaneous, the infrared moisture balance is commonly used in tea factories in the manual version. It is a gravimetric method that can be related directly to the reference method. An infrared lamp heats the sample for a set time, or until the rate of weight loss becomes very small. The distance of the lamp from the sample, and the voltage supply to the lamp, are critical factors in ensuring that all moisture is lost without burning off more of the sample than would occur in an oven. The method takes under 10 minutes for a dry tea sample and under 30 minutes for a dhool or leaf sample. The more recent development of such an instrument uses a thermostatically controlled infrared radiating element, and an electronic balance with a microcontroller which sequences the whole operation, switches off the heat at the end and calculates the moisture content. Often these instruments have a serial port for transfer of data to a computer.

A much more sophisticated approach is found in near infrared reflectance instruments. These irradiate a sample with infrared light at low intensity, with an insignificant drying effect. The reflected or back-scattered light is measured at specific wavelengths, and the absorbance calculated. Different classes of molecules absorb infrared light at different wavelengths, dependant on the bond energies. Water molecules absorb certain wavelengths, so this absorbance will give an indication of the amount of water in the sample. Other measurements are required to determine the amount of dry matter present. This method can be extended to measure molecules other than water. The results are reported almost instantaneously, and as it is a non-contact method, it is very suitable for use on line in a continuous process plant.

Hall *et al* (1988) used a laboratory-type instrument to investigate the prediction quality of near-infrared reflectance for moisture, quality and theaflavin content of black tea. They found reasonable correlations for all factors tested, but the scatter of points for moisture measurement was too wide for use in dryer control. To determine an analytical method for use with near-infrared reflectance requires the selection of filters, some of which are sensitive to the moisture only, and some of which are sensitive to a constant dry matter constituent only. The fewer filters used, the more robust the calibration is likely to be over a wide range of materials. Hall *et al* found that a high fibre content sample was the cause of outliers when analysing for moisture content; for dryer installation, the calibration has to be able to handle varying amounts of fibre.

Two types of infrared moisture balance and two types of near-infrared absorption moisture analysers were used in this work. The objective for each type was to find the settings for operation in two main zones, wet dhool in the region of 72% m.c. w.b. and made tea at dryer discharge, in the region of 3% m.c. w.b., forming the supply of material to be dried and the final product.

For the on-line type of instrument, a secondary objective was to obtain a continuous calibration over the whole range from 75% or more down to below 3%. If an instrument could measure over this full range, then batch drying could be monitored continuously and so validate a model of the process.

13.2 Moisture balance calibration

Instruments from Mettler and Ohaus were used in this work. The Ohaus MB200 was calibrated first. Both instruments work by continuously weighing a sample, which is heated by infrared radiation from a metal sheathed element. A temperature sensor, which is placed between the element and the sample, controls the temperature to which the sample is exposed. The Ohaus uses a stainless steel sheathed thermocouple while the Mettler appears to measure infrared radiation from the sample.

The whole unit is microprocessor controlled, and can be programmed to operate in different modes. The simplest is to expose the sample to a fixed temperature for a fixed time, and to report the moisture content as the weight loss during the drying time. As a more sophisticated way of determining the endpoint of the drying, the instrument can be programmed to stop drying after the drying rate has dropped to a programmed level, such as 10 mg per 10 s.

This latter mode is likely to provide the fastest and most accurate method of determining moisture, but the problem arises in which values to use in the program. The tests carried out here had the initial aim of determining these values.

13.2.1 Materials and methods - Drying curves

The first tests were to investigate the drying rate of already dried tea, to see if the drying rate could be set for a constant time at a constant temperature, the simplest mode of operation of the moisture balance. The temperature to be used and the repeatability of runs could also be investigated.

A series of tests was carried out on samples of made tea taken from a bulk of dryer mouth tea which had been stored under ambient conditions for two months and had reached equilibrium with the ambient atmosphere. Oven moisture content at 105°C (ISO method) of the bulk gave a moisture content of 8.5% wet basis.

Because the Ohaus MB200 is equipped with a serial interface, it was possible to download values for weight, temperature, elapsed time and moisture content to a computer. A simple program was written to record these data in a comma separated value file.

Samples of at least 10 g (as recommended by the manufacturers for adequate resolution) but less than 12 g (to avoid having too deep a layer on the pan) were measured onto the pan using the readout on the MB200. Temperatures from 45 to 170°C were used, in 5° intervals up to 150°C and 10° intervals above. The single temperature, fixed time program was used for all measurements. At the lower temperatures, the time was 45 minutes, reducing to 10 minutes at the highest temperatures. Each run was repeated at least once.

All runs were carried out over a period of 3 days when the weather was consistently dry and the ambient relative humidities were around 40%.

13.2.2 Results

The data collected were assembled into a spreadsheet, and using the oven moisture measurement, the actual moisture content of each sample for each data point was calculated. Then, the rate of loss of moisture was calculated as percentage of water present at the start of a 60 s period which was lost at the end of the period. The average temperature measured over the same 60 s period was calculated.

These results were then arranged in order of exposure temperature and moisture content, and the average of moisture loss rates for the same temperature (degree intervals) and moisture content (1 % moisture intervals) was calculated. After this averaging, there was still an extensive set of data, so the values for each moisture content were further averaged over 10° intervals.

The values near the middle of the temperature and moisture ranges are made up of tens or hundreds of readings averaged, while some at the extremes consist of only a few readings. Fig. 13.1 shows moisture content (calculated by weight loss from initial oven moisture content) against time.

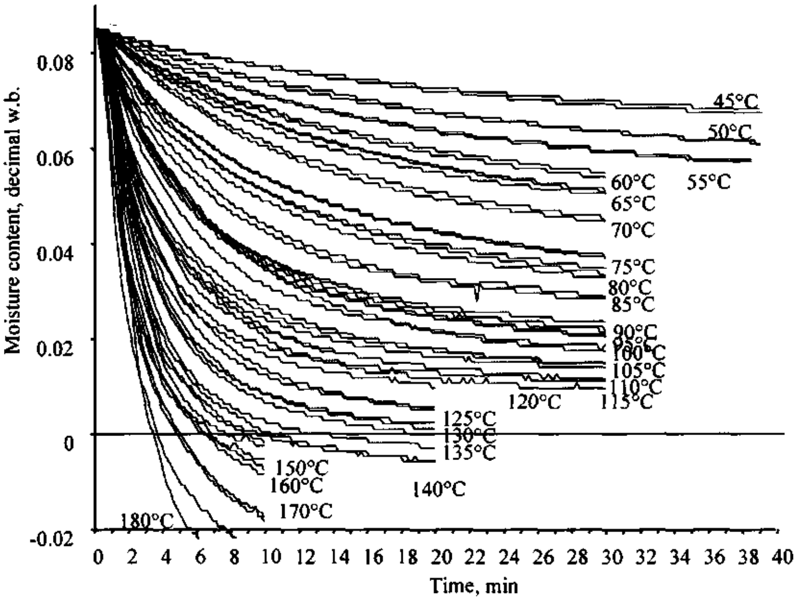

Fig. 13.1 Weight loss curves for Ohaus MB200 at varying temperatures.

One feature of the above plot which is very satisfactory is the repeatability of the results. The curves for the pairs of runs lie almost on top of each other. The major cause of differences can only be seen when the starting minute of the graph is expanded. Then the difference between starting the instrument from cold and starting immediately after a previous sample with the instrument hot can be seen.

It is clear that at temperatures above 120°, more than moisture is being lost as the values go negative. At 160 and 170°C, the sample was seen to smoke soon after starting the run, and even at -1% the rate of loss was still high, indicating that this could amount to the majority of the sample.

Because the reference method is defined at 105°C, extended drying above 105°C is not very meaningful. It explains also the final negative values for the high temperatures because other components will be lost. To develop the method for rapid determination, a temperature needs to be determined at which moisture loss is rapid, but can be arrested at the same level as oven drying at 105°C.

At indicated temperatures of 110° and less, it is unlikely that a true moisture content would be measured even after 1 hour or more. The equilibrium relative humidities need to be determined at each temperature, as the drying will not proceed past the equilibrium point at that temperature.

Table 13.1 shows the final averages of the rate of loss of moisture as a percentage per minute of what was present at the start of the minute, for varying temperatures and moisture contents. It might be expected that the drying rate would reduce as the sample loses moisture as predicted by standard drying theory, giving a positive slope to the line of rate against moisture content.

Table 13.1 Moisture loss rate per minute for varying temperature and varying initial moisture.

Moisture % wb	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Intercept**	**slope**
Temp.°C											
50						0.02	0.01	0.02	0.03	-0.01	0
60						0.02	0.03	0.05	0.05	-0.04	0.01
70					0.03	0.03	0.06	0.08	0.06	-0.01	0.01
80			0.02	0.03	0.06	0.09	0.13	0.13		-0.04	0.02
90			0.04	0.08	0.14	0.19	0.25	0.18		-0.02	0.04
100		0.05	0.06	0.14	0.2	0.27	0.25			-0.01	0.05
110		0.06	0.19	0.34	0.37	0.46	0.34			0.07	0.06
120	0.04	0.11	0.26	0.31	0.43	0.41				0.05	0.08
130	0.34	0.4	0.51	0.68	0.57	0.47				0.4	0.04
140	0.97	0.77	0.87	1.03						0.87	0.03
150	1.33	1.03	1.08	0.89	0.61					1.3	-0.16
160	1.43	1.06	1.16	0.82						1.38	-0.17
170	2.27	1.19	1.14							2.1	-0.57

A simple linear regression was carried out to find the slope and intercept for each temperature, and the results are shown as the final two columns in the table.

The results do not give a family of parallel rate curves as might be expected. At the lower temperatures, the slope of the drying rate versus moisture content line is least, indicating that the wetter tea dries less rapidly at lower temperatures.

The steepest rate of change of drying rate with moisture content is at 120°C. Beyond this temperature, the slope of the curve reverses, and the tea dries more quickly the drier it becomes. As this is completely contrary to drying theory, the only explanation is that as the sample heats up, it starts to lose more than water, and this faster rate at lower moistures is a prelude to burning.

There is not enough span of readings particularly at the higher temperatures to have confidence in the actual values of slope, but the trend in slope is very clear, and the change to a negative slope at higher temperatures cannot be disputed.

It is difficult to determine the relationship between the indicated temperature and the tea temperature. The layer is too thin to permit a standard probe to be inserted in the layer without touching either the foil pan or being exposed to direct radiation from the heating element. The heating chamber is too small to permit the use of an infra red thermometer, and there is no space to construct a viewing port.

It is possible to insert a fine wire thermocouple into the dhool, but this affects the weight reading so cannot be used during moisture determination. Table 13.2 shows the results obtained with the temperature set at 100°C, with 11 g of tea on the pan.

Table 13.2 Comparison of system sensor with tea temperature measurement

Time from start, min	**5**	**10**	**15**
Ohaus temperature reading, °C	102	101	100
Thermocouple temperature reading, °C	80	85	88

Thus the temperature sensed will only reflect the material temperature after a significant drying time. For shorter drying times, higher temperatures than would normally be used in oven drying can be set without risk of over drying.

An initial high temperature can be used to start off the drying, but values above 150° should not be entertained for more than a minute, the time it takes for the tea to reach the set temperature. Further tests detailed below were used to determine the optimum parameters.

13.2.3 Tests with re-wetted tea samples.

In order to repeat a standard set of measurements, particularly below the range of moistures normally encountered, some samples were made up of known moisture content by drying tea and then adding a known quantity of water. Enough of each moisture content was made to allow repeated measurements. To determine the correct temperature for measurement, a sub-sample of each moisture content should be measured at each temperature. When the measured value equals the actual value, the correct temperature for that moisture content has been found.

A bulk sample of tea from a fluid bed dryer, of about 1 kg, was collected and placed in an oven at 105°C for 36 hours to take it to dryness. Subsamples of 100 g were weighed into plastic jars, and distilled water was added to make the samples up to 1, 2, 3, 4, 5, 6, 7, and 8% moisture content. The jars were stored for 10 days, and thoroughly agitated on every second day to ensure an even distribution of moisture within the sample.

These samples were then sub-sampled and moisture tested using the MB200. Tests were performed using the auto-dry program, with settings of 150, 145, 140, 135, 130 and 125°C for each moisture content. The end point was set at the lowest drying rate to which the instrument could be programmed, 0.01 g loss in weight in 1 minute. All samples weighed between 10.0 and 10.5 g. The results were logged onto computer disk. Table 13.3 summarises the results.

Table 13.3 Moisture measured for various actual moisture contents and temperatures.

MC %	8	7	6	5	4	3	2	1
Temperature	Moisture measured							
150°C	7.9	7.4	6.1	5.7	4.3	3.9	3.2	2.1
145°C	7.9	7	6	5.1	4.6	3.9	3.1	2
140°C	7.7	6.5	5.5	4.9	4.3	3.5	2.5	1.7
135°C	7.5	6.7	5.4	4.8	4.2	3.2	2.5	1.6
130°C	7.2	6.6	5.3	4.7	4.2	3	2.3	1.5
125°C	6.9	6.2	4	4.9	3.8	2.9	1.4	1.2

To determine the correct temperature for each moisture content, a graph is plotted from Table 13..3 to give Fig. 13.2, on which the actual results are shown; the measurement tolerances of plus and minus 0.5% are shown as parallel solid lines.

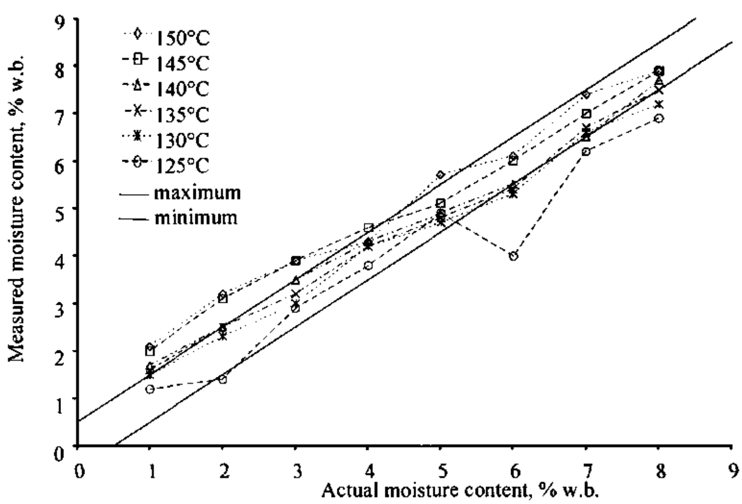

Figure 13.2 Graph of indicated against actual moisture contents at varying temperature.

The results for the 6% sample were all low, particularly for the 125°C run, so there may well have been an error in making up this moisture content.

An ideal calibration would give a line of slope 1, so at that temperature, whatever the actual moisture, the predicted value would be correct. Other methods could be used, but would require a calculation from the indicated moisture content to give the actual moisture content. By selecting the temperature to give the calibration, the moisture content given by the instrument can be used directly.

From the graph the slope of the curves is less steep than ideal, so a temperature must be selected to suit the region where the greatest accuracy is required.

Regression analysis of the slopes was performed on the lines, and reported in Table 13.4 which shows one set of results including all readings and the second set excluding the suspect 6% sample.

The standard errors and R^2 are improved by dropping the 6% samples. The average standard error of the intercept improves from 0.258 to 0.188, of the slope from 0.0399 to 0.0300 and the average R^2 improves from 0.9788 to 0.9914. The following discussion uses the data excluding the 6% samples.

The intercept increases with increasing temperature, while the slope is more or less constant at an average value of 0.836. A further regression analysis of intercept against temperature gives a result that: $Intercept = -5.09 + temperature(°C) \times 0.0434$
The adjusted R^2 for this analysis is 0.93.

Table 13.4 Regression results of moisture calibration curves at varying temperatures

Including 6% samples

Temperature °C	150	145	140	135	130	125
Constant	1.35	1.33	0.9	0.76	0.66	0.25
Std Err of Y estimate	0.24	0.17	0.19	0.17	0.18	0.59
Coefficient	0.83	0.8	0.82	0.83	0.82	0.81
Std Err of Coefficient	0.04	0.03	0.03	0.03	0.03	0.09
R^2 (Adjusted)	0.986	0.992	0.991	0.993	0.992	0.918
No. of Observations	8	8	8	8	8	8
Degrees of Freedom	6	6	6	6	6	6

Excluding 6% samples

Temperature °C	150	145	140	135	130	125
Constant	1.34	1.32	0.89	0.75	0.65	0.2
Std Err of Y Estimate	0.24	0.17	0.15	0.1	0.15	0.32
Coefficient	0.84	0.81	0.83	0.84	0.83	0.86
Std Err of Coefficient	0.04	0.03	0.02	0.02	0.02	0.05
R^2 (Adjusted)	0.988	0.993	0.995	0.998	0.995	0.979
No. of Observations	7	7	7	7	7	7
Degrees of Freedom	5	5	5	5	5	5

Using these values to plot a similar graph to the previous one, but showing only the segments of the curve within the +0.5%/-0.5% tolerance band yields Fig. 13.3.

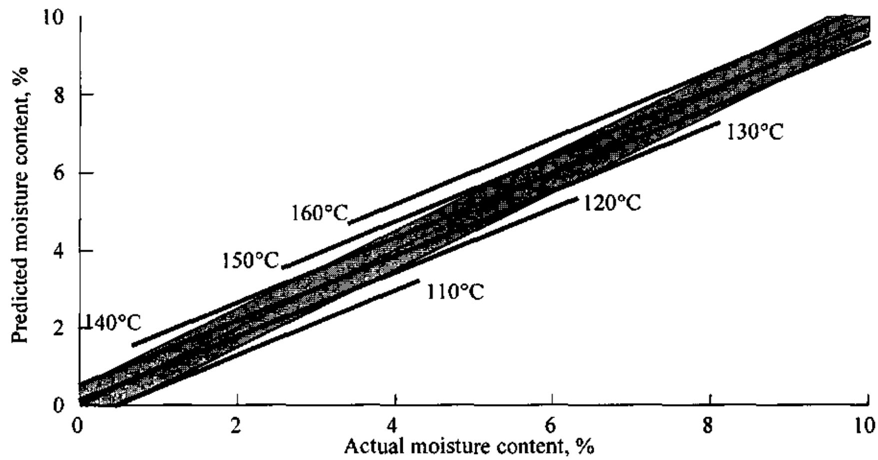

Figure 13.3 Graph showing selection of temperature for analysis of varying moistures.

This allows us to select a temperature to obtain the most accurate results for any given moisture range, as shown in Table 13.5.

Table 13.5 Selection of temperature for most accurate moisture measurement.

Temperature set °C	**110**	**120**	**130**	**140**	**150**	**160**
Maximum accuracy	<0	1	3.5	6	8.5	>10
Lowest acceptable	0	0	0.5	3	6	9
Highest acceptable	0.75	3.5	7	9	>10	>10

The recommended setting for made teas is therefore:

Auto dry mode, Temperature: 130°C, Weight loss: 0.01 g, Time for weight loss: 60 seconds.

The reason the setting is so critical around the 3% moisture content is that the finest resolution is 0.01 g, and for 3% moisture a total weight loss of only 0.3 g from a 10 g sample is measured so the moisture resolution cannot be better than 3 % (0.01 g in 0.3 g) while dry matter resolution is 0.01 g in about 10 g or 0.1%. For dhool moistures, about 7 g out of a 10 g sample will be lost, so moisture resolution is 0.01 g in 7 g (0.14%) and dry matter resolution is 0.01 g in 3 g (0.3%), giving an order of magnitude better results.

To improve accuracy, higher pan loadings can be used but these have the disadvantage that drying time is extended, and the thorough drying of the bottom layer is uncertain.

13.2.4 Dhool moisture measurement

For dhool, the ratio of water to dry matter is very much higher, making dhool moisture measurement simpler. The objective at this moisture content is to be able to measure to the nearest 0.5% moisture content wet basis over the range 68% to 75%. This is the level of accuracy required for control of the tea manufacturing process, and covers the range of moistures normally encountered during processing before drying. The ratio of water to dry matter is very similar over this range, so once the setting has been determined for one moisture content it is likely to apply to the whole range.

This is fortunate, because re-wetting techniques are inappropriate for high moisture contents. To determine the optimum settings for dhool, samples were taken from the twin lines fermenters during production on one day. Each sample was well mixed by hand, then between 10 g and 11 g were loaded onto the pan of the MB200. Auto dry mode was selected, with temperatures between 130°C and 180°C, and a weight loss of 10 mg in 60 seconds. The sample was analysed, and the data output was recorded on a computer. From the remainder of the same sample, about 30 g was put in a moisture sample tin and the lid firmly fitted. These samples were dried overnight in an oven at 105°C to determine the moisture content.

The results are shown in Table 13.6. All moisture contents are expressed as % wet basis. The range of temperatures tested here are higher than in the dry tea experiments, as there is much more moisture to evaporate, requiring more energy, and also leaving a much lower mass of dry matter at the end of the experiment. A higher temperature gives a more rapid moisture loss. As the end point in Auto mode is determined by a fixed weight loss per unit time, rather than as a proportion of the sample, the more rapid drying should give a better end point. If there is a proportion of volatiles lost, as the water lost is so much greater, these volatiles will represent a much smaller proportion of error.

A regression analysis of error against temperature gave an adjusted R^2 of 0.91. These data are plotted in Fig. 13.4, which clearly shows that the optimum setting for dhool is 150°C, in Auto Dry mode with a weight loss of 0.01g in 60 seconds. Measurements will be expected to take about 24 minutes.

Table 13.6 Dhool moisture content error on Ohaus MB200 at increasing temperature

MB 200 Set temperature °C	oven MC	MB200 MC	Error	Time on MB200
130	69.48	69.1	0.38	33
130	70.53	69.8	0.73	30
140	70.77	70.4	0.37	29
140	70.52	70.2	0.32	31
150	69.72	69.6	0.12	24
150	69.06	69.3	-0.24	23
160	56.61	57	-0.39	not recorded
160	72.15	72.1	0.05	26
160	70.83	71.1	-0.27	19
170	69.1	69.7	-0.6	20
170	55.84	56.6	-0.76	18
170	73.73	74.3	-0.57	22
180	68.11	69.1	-0.99	18
180	68.61	69.5	-0.89	20
180	59.94	61.2	-1.26	16

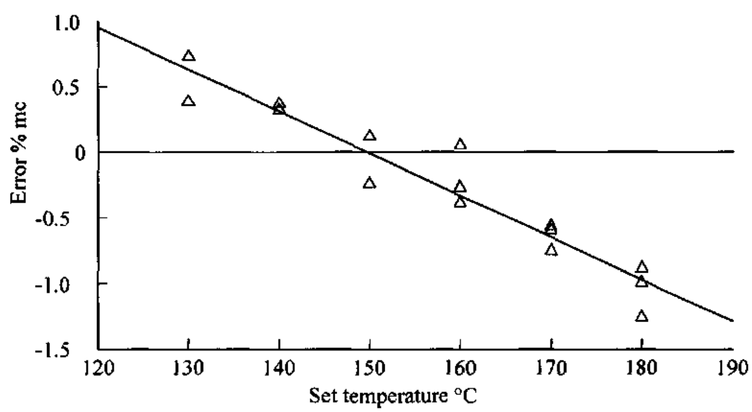

Figure 13.4 Graph of moisture content error against temperature setting.

13.2.5 Leaf moisture measurements.

Because the moisture content reaching the dryer is not changed substantially between maceration and drying, to control the moisture of the dhool reaching the dryer it is necessary to measure the moisture content of the whole shoots. As these have the same moisture content range as the dhool, the same temperature settings might be found to apply; however the much lower surface area for evaporation might affect results.

Preliminary measurements made on entire leaves or shoots show that they cannot be measured directly, as they protrude above the pan, contacting parts of the hood and influence the weight measurement. Chopped leaf works better (chopped by scissors), but if there is more than one layer of leaf on the pan, the top leaf dries and seals the moisture into the leaf on the lower layer. This problem is overcome by the use of a metal gauze or mesh pan which allows moisture to escape downwards as well as upwards. The test pan was made of perforated metal, but any lightweight open mesh material which is resistant to the temperatures used would be suitable. The foil trays supplied with the machine have a diameter of 120 mm and a depth of 3 mm; if the mesh pan had a similar diameter but a depth of 10 mm this would prevent parts of leaf touching the pan shield and affecting the weight readings. Results from the tests are shown in Table 13.7.

Apart from one reading at 1.8% mc error, taken at 160°C, all readings were within 0.8% of the oven reading. The leaf with an average oven moisture content of 76.8% varied between 76.5 and 77.1 oven moisture, in samples of about 50 g. For the MB200 readings to come within a range of +0.5% to -0.8%, apart from one, on only a 10 g sample, is a very acceptable result considering the variablility in shoot moisture. An analysis of error similar to that done with dhool, with a regression line is shown in Fig. 13.5.

Table 13.7 Chopped leaf moisture content error on Ohaus MB200 at increasing temperature

Set temperature °C	Time to finish minutes	Measured MC % wb	Oven MC % wb	error
150	34	76.9	76.8	-0.1
150	36	76.9	76.8	-0.1
160	30	77.4	76.8	-0.6
160	39	78.6	76.8	-1.8
140	52	76.8	76.8	0
140	42	78.5	77.7	-0.8
150	34	77.8	77.7	-0.1
145	43	77.2	77.7	0.5
145	41	78.2	77.7	-0.5
155	36	78.4	77.7	-0.7
155	40	78.5	77.7	-0.8
150	38	77.6	77.7	0.1

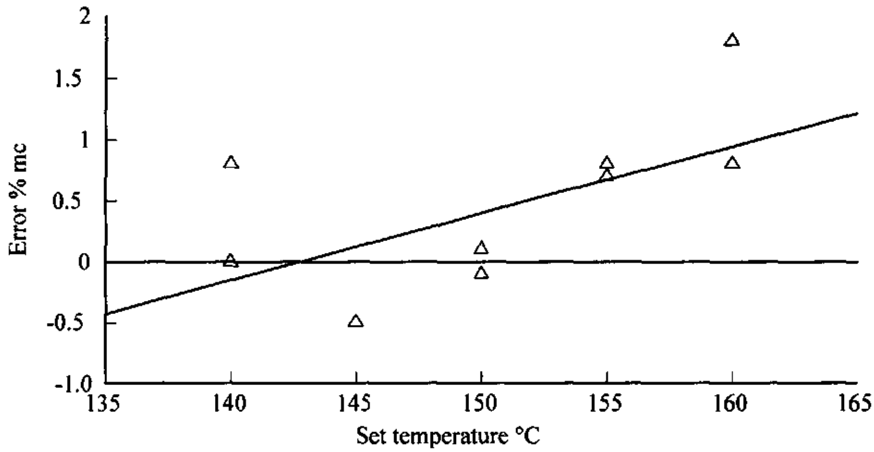

Figure 13.5 MB 200 leaf moisture analysis auto dry mode. Error in moisture at different temperatures

Again the optimum temperature setting is around 150°C. Because of the variability in sampling leaf for moisture content, (unlike dhool which is thoroughly homogenised and mixed before analysis), and the fact that the same sample used for the standard cannot be used in the test, the results are as good as can be expected with such a small sample size. The only way of improving the accuracy with leaf would be to use a machine which can accept a much larger sample.

13.2.6 Mettler LJ16 moisture balance.

As the Ohaus MB200 had been calibrated against the reference method, the LJ16 was calibrated against the Mettler-method. Samples were split between the two instruments, and an auto-dry mode temperature was selected for the Mettler which gave equivalent values to the Ohaus. As the temperature sensing was different on the two instruments, different temperature settings were anticipated. Dry teas around 3% moisture required a temperature setting of 105°C, while dhools and chopped leaf required 120°C. Following this initial determination of temperature settings, samples were run in parallel on the two instruments at regular intervals. An example of the comparisons is shown in Table 13.8. The differences are minor, and of the same order of magnitude as sampling error.

Table 13.8 Comparison of results from two moisture balances.

Ohaus at 150°C	71.4	70.8	69.9	69.5	68.8	68.3	67.8
Mettler at 120°C	71.0	70.3	69.7	69.3	68.5	68.2	67.7
Error	+0.4	+0.5	+0.2	+0.2	+0.3	+0.1	+0.1

13.3 Calibration of near infrared absorption moisture meters.

Instruments were purchased from two manufacturers, Infrared Engineering (Model MM55E) and Moisture Systems (Model MicroQuad MQ8000). The intention of these instruments was monitoring the progress of batch drying, possibly looking at diffusion rate by comparing infrared moisture measurements from the surface with weight measurements giving an average, and for production and control system monitoring.

Each system had an electronic control box, which could be connected to the sensing heads by cable. The sensing heads were designed for mounting above a conveyor or similar part of a process plant.

13.3.1 Principle of operation

A light bulb, run at a lower voltage than normal, produces less visible and more infrared radiation than when run at its rated voltage. The light is directed onto the sample, and the reflected light is focused onto a detector sensitive to infrared. Between the focusing and the detector, a wheel containing several narrow bandwidth filters is interposed. The wheel rotates, chopping the signal to the detector and presenting the filters in sequence to the light beam. A second beam, direct from the light source but suitably attenuated, is also sent to the detector (or a separate detector), to give a reference value.

The output from the detector is signal conditioned, then processed by the electronics according to an algorithm programmed into the system. The result is displayed on a digital display, and is available in analogue or serial data form for data logging.

13.3.2 Methodology

Both instruments were supplied with filter wheels containing a selection of filters considered by the makers to be suitable for moisture analysis on made teas. Using the calculation algorithm pre-programmed into the system, preliminary data could be obtained. By comparing the value from the instrument with a value from the reference method, a revised span or slope, and offset or zero intercept could be obtained (i.e. an instrument calibration procedure). When these revised values were entered into the calculation algorithm, the output should then correspond with the reference method.

For a calibration to be robust, that is, to maintain accuracy over a wide range of samples, the range of samples presented during calibration must be at least as diverse as to be used in practice. For tea this meant using several clones, different methods of maceration, different fermenting times, different fibre percentages, and as many other variables as could be envisaged.

There are other potential variables, such as how the sample is presented to the instrument in terms of surface roughness. To reduce this influence, a sample can be placed on a small turntable, so several readings can be taken of a different part of the surface of the sample.

13.3.3 Initial tests

The first tests were run in the hope that there would be a full range calibration for monitoring batch drying.

Many tests were run using the Infrared Engineering MM55 system. Often some good correlations would be found, such as in Fig. 13.6. Here the need for slope and intercept correction can be clearly seen, and it appears that the data set would fit a curve better than a straight line. Unfortunately there is no way of entering anything other than a straight line calibration into the system; the best that can be done is to choose a small region of interest and use the values from this part of the curve only.

For the data taken on one particular day, satisfactory calibrations with satisfactory standard errors could be obtained over a limited span, such as from zero to 10 or 20% moisture. However, after several sets of calibration data had been taken, different slopes and intercepts were found each time. There were at least three different factors which could be causing this shift in calibration: different degrees of fermentation, different proportions of fibre, or characteristics of different clones. The Moisture Systems MQ8000 instrument behaved in a similar fashion. It was necessary to identify a different reference wavelength to that used in the two instruments, which would measure a substance which was less variable.

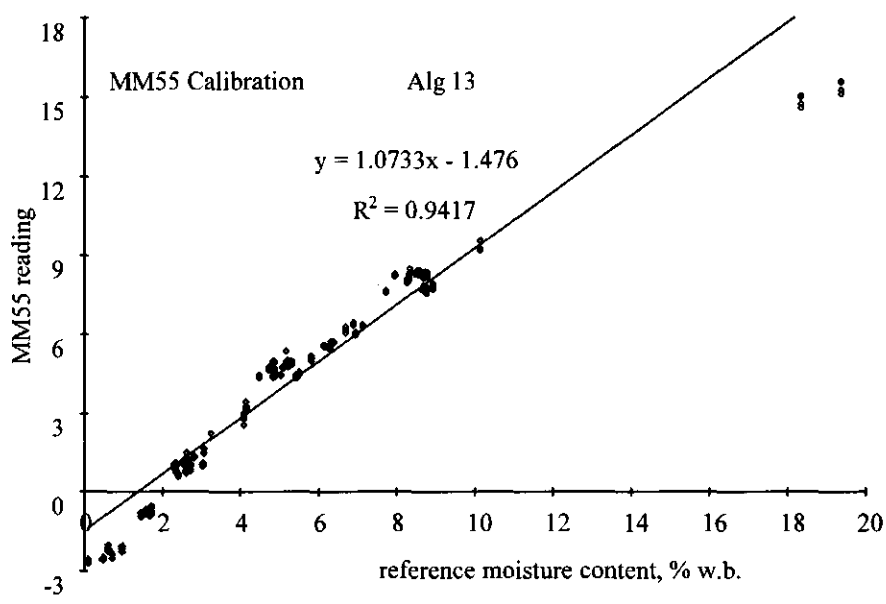

Figure 13.6 Graph of reference moisture measurement and MM55 moisture measurement.

For the data taken on one particular day, satisfactory calibrations with satisfactory standard errors could be obtained over a limited span, such as from zero to 10 or 20% moisture. However, after several sets of calibration data had been taken, different

slopes and intercepts were found each time. There were at least three different factors which could be causing this shift in calibration: different degrees of fermentation, different proportions of fibre, or characteristics of different clones. The Moisture Systems MQ8000 instrument behaved in a similar fashion. It was necessary to identify a different reference wavelength to that used in the two instruments, which would measure a substance which was less variable.

13.3.4 Use of Infraalyzer

The next step was to look at alternative wavelengths to those provided in the commercial instruments.

The Bran+Luebbe Infraalyzer 450 off-line instrument, using 19 filters rather than the 5 in the on line instruments, was used to investigate the best filter sets for moisture determination. A set of 59 varied samples was presented to the instrument, and the data analysed. The filter selections are shown in Table 13.9; filters that were not selected have been omitted from this table. First, the software chose the measuring wavelength. This used 1982 nm as the measuring wavelength, which has no chemical relationship to water and is therefore not likely to be robust. The water wavelength of 1940 nm was set as a forced value, indicated by the letter "f" in the table. To select the best filter combination, the F value shown in the table should be the first selection parameter. A negative value indicates that the value of the filter is subtracted from the model, rather than being added.

Table 13.9 Infraalyzer filter selection on set of 57 black teas

	No forced filters					**Force 1940**							
No of filters	**2**	**2**	**2**	**2**	**3**	**2**	**2**	**2**	**2**	**3**	**3**	**4**	**4**
Filter													
2270					-1								-1
2230		-1					-1					-1	
2208	-1					-1							
2190			-1					-1					
2139									-1				
2180				-1									
1982	1	1	1	1	1							1	1
1759										2	2		
1940						f	f	f	f	f	f	-f	-f
1734											-2		
1722										-2			
1680					-1							-1	-1
R^2	0.973	0.973	0.972	0.971	0.981	0.967	0.967	0.967	0.966	0.975	0.973	0.981	0.981
F	498	488	470	460	460	400	400	397	394	352	328	347	346
SE	0.548	0.553	0.563	0.568	0.469	0.607	0.607	0.609	0.611	0.533	0.551	0.468	0.468
RSD	0.538	0.543	0.553	0.558	0.456	0.596	0.596	0.598	0.601	0.519	0.536	0.451	0.452

The larger the F value the more robust the calibration; it is better to have a larger F even at the expense of a larger Standard Error or Residual Standard Deviation, as the calculation of F takes into account the number of filters employed. From this table, it was concluded that a filter in the region of 2200 nm should be tried in the on line instruments.

13.3.5 Moisture Systems revised filter set

A filter wheel was installed in the Moisture Systems instrument, utilising the wavelengths suggested by the experiments on the Infraalyzer. Presenting samples to this instrument gave a good calibration with a standard error of less than 0.4, using 1940 nm as the moisture measuring wavelength and filters in the region of 2200 and 1820 nm for the reference measurement (13.7).

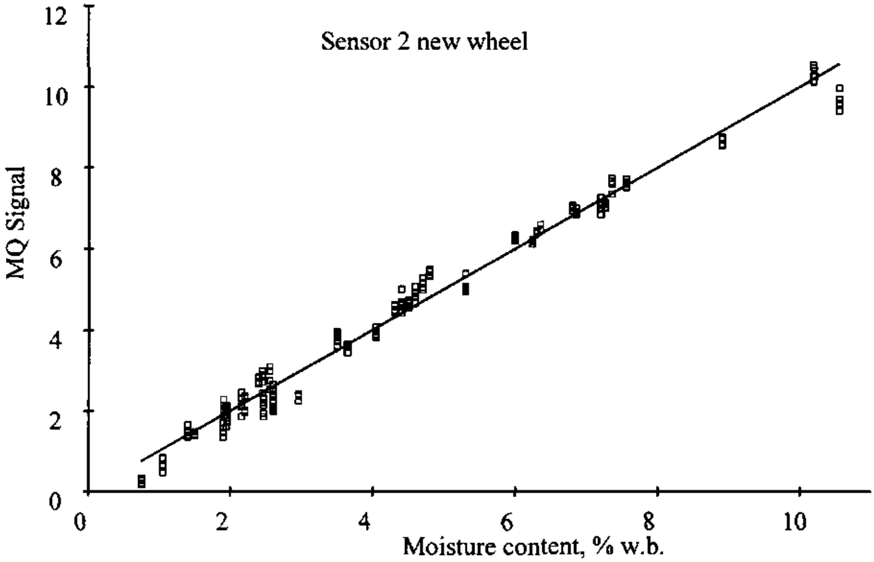

Figure 13.7 Calibration of black tea with revised filter set, Moisture Systems MQ8000. SE<0.4.

To extend the calibration to the full range of moisture contents encountered in a batch dryer (up to 75%), a new range of samples taken from a fermenter, and at various stages through a dryer were presented. To obtain a similar correlation to the dry teas, an additional filter had to be used, in the region of 2100 nm. This gave a correlation R of 0.991, but the standard error was high at 2.95 Looking at the calibration curve, Fig. 13.8 shows that the greatest extent of spread of values is at the wet end of the graph. This might be due to differences in fermenting time, or different presentation of the fibre in the sample.

Although this calibration was not perfect, it was repeatable and could be relied on for measuring intermediate moistures during drying experiments. It was not accurate enough for dhool moisture measurement, as a feedforward measurement for dryer control, as the spread of indicated values was greater than the normal range of expected values.

Subsequent calibration checks confirmed this selection of filters, and the instrument was used for on line dryer discharge moisture measurement as well as following the moisture during batch drying. For the latter application, as the instrument was exposed to the dryer exhaust air containing eluted fibre particles, an air purge of the light beam and water cooling were provided.

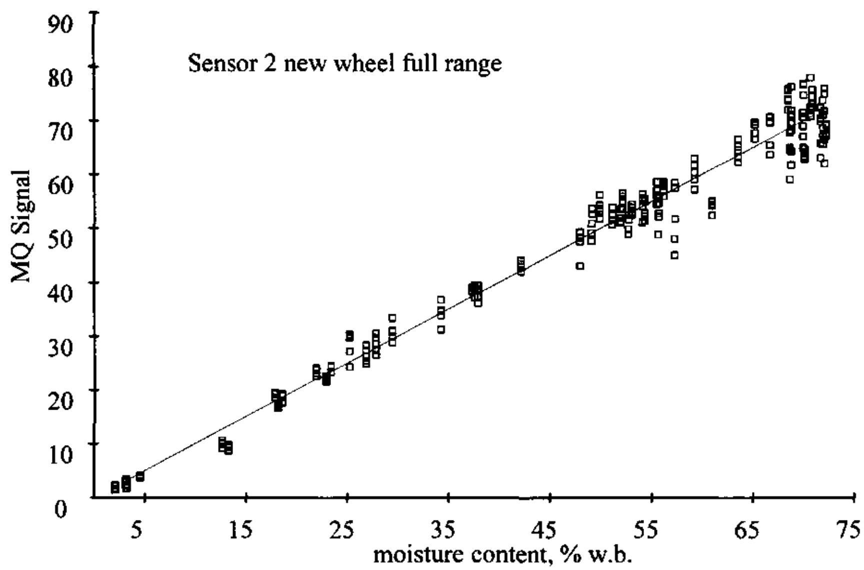

Figure 13.8 Full range calibration with revised filter set, Moisture Systems MQ8000.

13.3.6 Infrared Engineering MM55

A set of filters similar to those used in the Moisture Systems instrument was installed. However, no significant improvement over the original settings was obtained. The reason for this might be due to the exact filter specifications, which differ from one manufacturer to another. Neither manufacturer divulges the precise wavelength and bandwidth of the filter.

13.3.7 Use on whole leaf

Some preliminary trials were performed using whole leaf, to see if the system could be used for control of withering. The response from the upper and lower leaf surfaces was totally different. The upper surface is waxy, and produces direct reflections rather than diffuse backscatter. The lower surface has leaf hairs, and responded in a different way. For a bulk of leaf which read around 70% moisture on the instrument after maceration (about correct), the intact leaf read 0% moisture for the upper surface and 30% moisture for the lower surface. Even if an improved algorithm could be found which gave a more accurate value for the lower leaf surface, it would be very difficult to eliminate the effect of specular reflection from the upper surface.

13.4 Conclusion

Near infrared reflectance moisture metering is very attractive because of its instantaneous reading, and its potential for on-line application. A calibration was possible for dry, black teas with an acceptable level of accuracy using one make of instrument. For dhools, no setup could be found which was precise enough for control applications, and the use of the system on withered leaf was impractical.

Unfortunately the system is very costly (in the region of £8000 per sensor), and for the degree of accuracy available cannot be considered commercially viable for dryer control. It is the only method for experimental moisture measurement during a drying experiment, and the relatively poor performance at the start of drying can be compensated by changing to a more accurate algorithm below 10% moisture content.

The infrared heated moisture balances, once calibrated for dry teas and dhools, were as accurate as sample variation would allow. They are lower in cost than the on line system, but suffer the drawback of not being instantaneous. Results are available very much more quickly than the oven method, and are comparable in accuracy. Because they are an off line measurement method, they are unsuited to control applications.

For tea dryer control, there is no suitable method of moisture measurement for commercial application. To control the dryer, an inferential method must be used, which infers the moisture content from another measurement such as a temperature profile.

13.5 References

International Standards Organisation (1980) Tea - determination of loss in mass at 103°C. ISO Standard 1573

Hall MN; Robertson A; Scotter CNG (1988) Near-infrared reflectance prediction of quality, theaflavin content and moisture content of black tea. Food Chemistry, **27** 61-75

14 Appendix – Simulink model of 3 stage continuous fluidized bed tea dryer.

14.1 Introduction

A simulation model of a three stage continuous fluidized bed tea dryer was developed in the Simulink modelling system.

Table 14.1 Nomenclature and constants used in Simulink model

Symbol	Description	Value/units
P_atm	Atmospheric pressure at specified altitude	Pa
cpdm	Specific heat of dry matter	0.964 kJ/kg
cph20	Specific heat of liquid water	4.18 kJ/kg
lat_heat	Latent heat of water	2500 kJ/kg
cpvap	Specific heat of water vapour	1.805 kJ/kg
cpair	Specific heat of dry air	1.011 kJ/kg
ratefac	Drying rate correction factor for fluidized bed	0.6

14.2 Top level

At the top level of the model (Fig. 14.1), there is one block for each dryer section. The inputs to the first section are dhool temperature, dhool moisture content and feed rate. The ambient wet and dry bulb temperatures are fed into a calculation block (Fig. 14.2), which uses psychrometric equations to determine enthalpy and humidity ratio for the incoming air. The required air temperature, flow rate and bed plate area are fed separately into each block. The last block receives the weir height setting, which is effectively the maximum bed depth. After calculation, the actual bed depth is fed to the previous block (in the opposite direction to the flow of dhool).

Outputs of dhool moisture, mass flow and temperature are fed from one block to the next in the direction of dhool flow. These and other outputs, such as heater power required and air quality, are multiplexed to give a vector for each parameter. Residence time is calculated from the ratio of total mass of dry matter on the bed to the dry matter feed rate.

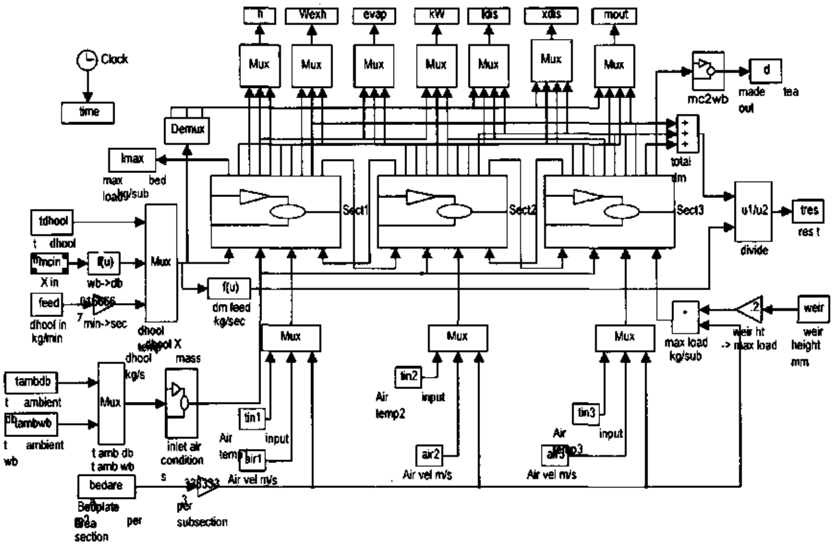

Fig. 14.1 Top level of the model

Block label	**Function**	**Formula**
wb->db	Convert moisture content from wet basis to dry basis	u/(100-u)
db2wb	Convert moisture content from dry basis to wet basis	100*u/(1+u)

The calculations for ambient air quality (Fig. 14.2) are based on the standard psychrometric equations.

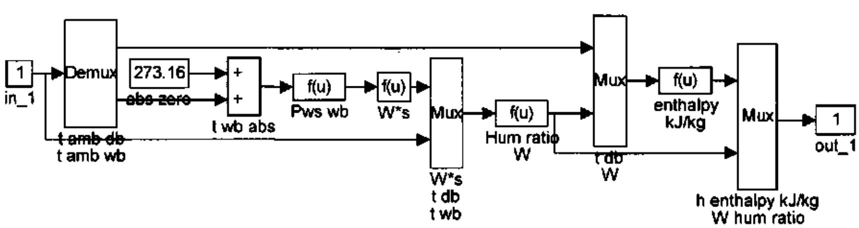

Fig. 14.2 Ambient air quality calculations

Block label	Function	Formula
Pws wb	Calculate saturation pressure at wet bulb temperature	exp(-5800.2206/u+1.3914993-.048640239 *u+.00004176476*u*u-0.000000014452093 *u*u*u+6.5459673*log(u))
W*s	Calculate humidity ratio at saturation	.62198*u/(P_atm-u)
Hum ratio W	Calculate actual humidity ratio	((2501-2.381*u[3])*u[1]-(u[2]-u[3]))/(2501+1.805*u[2]-4.186*u[3])
Enthalpy kJ/kg	Calculate air total enthalpy	u[1]+u[2]*(2501+1.805*u[1])

Each dryer section shown in Fig. 14.1 is split into three sub-units, as the dryer is operating closer to plug flow than to well-mixed conditions, and the division into these three sub-units gave a suitable approximation to the conditions found in practice. The inputs and outputs to each of the sub-units within a section, as shown in Fig. 14.3, is very similar to the arrangements for the individual sections. The main differences are that some of the outputs are summed or averaged to a single value rather than simply being multiplexed into a vector.

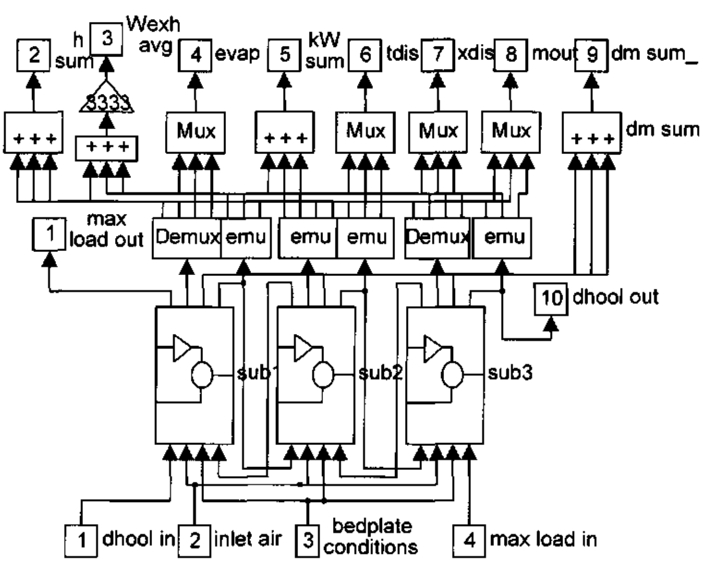

Fig. 14.3 Arrangements of sub-units within a dryer section

Within each sub-unit, the details of drying now start to appear (Fig. 14.4). There is a calculation block for the air heater, taking the inlet air conditions and raising the air to the required temperature, determining the power required to do so. The details of this block are shown in Fig. 14.5. The calculations are from the standard psychrometric equations. The humidity ratio at saturation and dry bulb temperature, W_{sdb}, and the saturation temperature, t_{sat}, may not be calculated directly so are determined from look-up tables calculated for the altitude specified when the model is initialised.

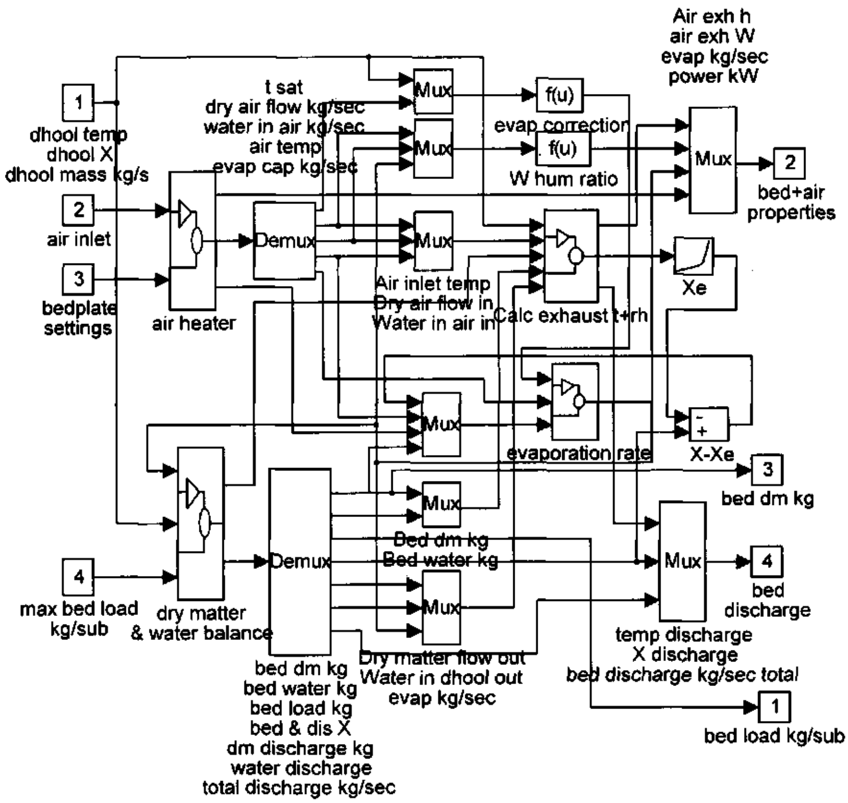

Fig. 14.4 Flow within a sub-unit

Block label	**Function**	**Formula**
Evap correction	Determine sensible heat available for evaporation	(u[4]-u[1])*((u[3]*cpdm/(1+u[2])) + ((u[3]-u[3]/(1+u[2])) *cph2o)) /lat_heat
W hum ratio	Calculate humidity ratio of exhaust air	(u[2]-u[3])/u[1]
Xe	Determine equilibrium moisture content of tea	Lookup table

Two of the three integrators that form the heart of the model are located in the dry matter and water balance block (Fig. 14.6) while the third is located in the enthalpy balance block (Fig. 14.7)

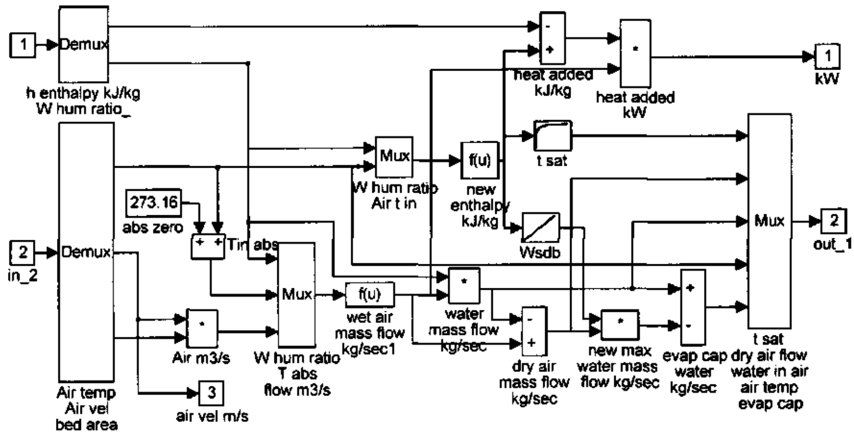

Fig. 14.5 Air heater

Block label	**Function**	**Formula**
Wet air mass flow kg/sec1	Calculate mass flow of wet air	u[3]*P_atm/(287.055*u[2]*(1 +1.6078*u[1]))
New enthalpy kJ/kg	Calculate enthalpy of air after heating to set temperature	u[2]+u[1]*(2501+1.805*u[2])
Tsat	Determine saturation temperature of heated air	Lookup table
Wsdb	Determine humidity ratio of saturated air at dry bulb temperature	Lookup table

The integrators that determine the dry matter and water balance are located together, as their behaviour is linked by the bed depth and weir height relationship. If the bed depth is lower than the succeeding stage, no mass is transferred to that next stage. If it is equal to the next stage, then the dry matter discharge combined with the water discharged is equal to the dry matter and water fed in less the evaporation in the stage. The switches that may be seen in Fig. 14.6 determine the choice between these two actions. Because of the interactions between the water and dry matter loops, a delay function is required to break the algebraic loop.

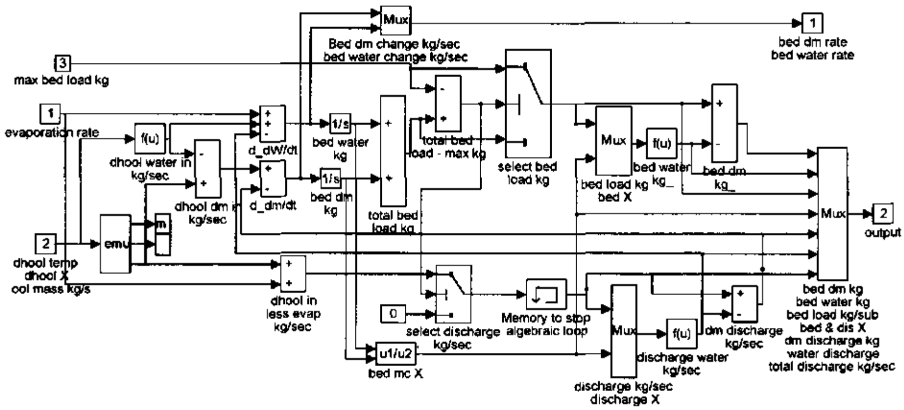

Fig. 14.6 Dry matter and water balance

Block label	**Function**	**Formula**
Dhool water in kg/sec	Convert wet mass flow and moisture content into water flow rate	u[3]*u[2]/(u[2]+1)
Bed load kg	Convert wet mass on bed into water on bed	u[1]*u[2]/(u[2]+1)
Discharge water kg/sec	Convert wet mass flow and moisture content into water flow rate	u[1]*u[2]/(u[2]+1)

The enthalpy balance integrator block does not have the interactions seen above, so appears much simpler (Fig. 14.7). The enthalpy of each component of the bed is calculated and summed. The integrator actually operates on bed temperature, the changes in which are determined by using the enthalpy and the mean bed specific heat (C_p). As the bed is considered to be well mixed vertically and have good heat exchange, the air exhaust temperature is taken as the same as the bed temperature.

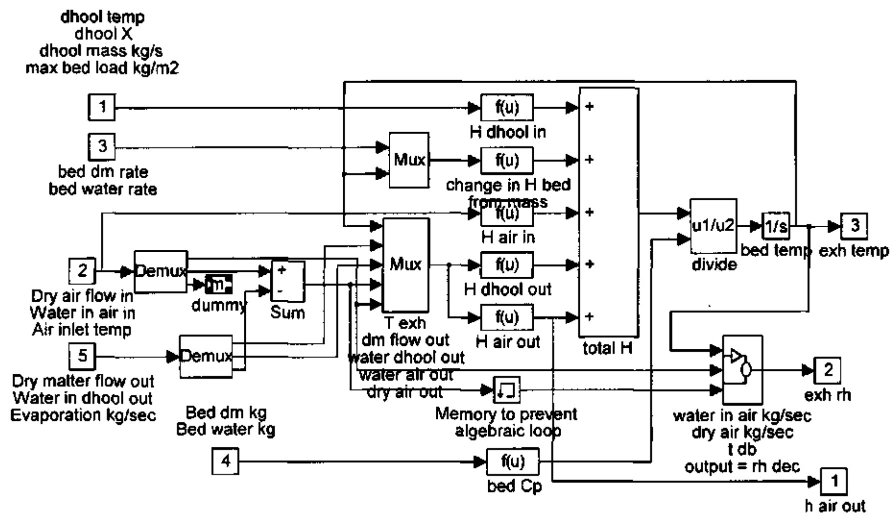

Fig. 14.7 Enthalpy balance

Block label	Function	Formula
H dhool in	Calculate enthalpy change due to influx of dhool from dhool properties	u[1]*(u[3]*cpdm/(1+u[2]) + (u[3]-u[3]/(1+u[2]))*cph2o)
Change in H bed from mass	Calculate enthalpy change due to change in mass of dhool on bed	-u[3]*(u[1]*cpdm+u[2]*cph2o)
H air in	Calculate enthalpy change due to air flow into bed	u[3]*(u[2]*cpvap+u[1]*cpair)+ u[2]*lat_heat
H air out	Calculate enthalpy change due to air leaving bed	-u[1]*(u[4]*cpvap+u[5]*cpair)- lat_heat*u[4]
H dhool out	Calculate enthalpy change due to dhool leaving bed	-u[1]*(u[2]*cpdm+u[3]*cph2o)
Bed Cp	Determine specific heat of material on bed	u[1]*cpdm+u[2]*cph2o

The inlet air properties and the exhaust temperature are used in a further calculation block expanded in Fig. 14.8. This is evaluates the exhaust air relative humidity. Note that another delay function is required in the input to this block as an algebraic loop breaker.

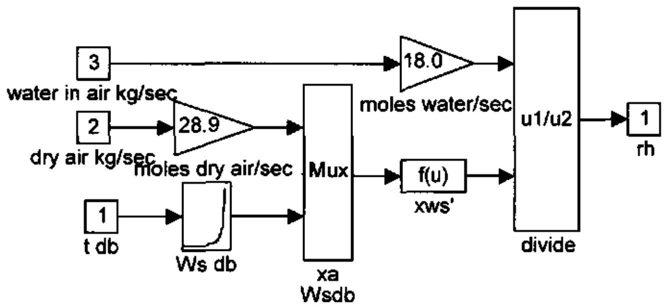

Fig. 14.8 Calculation of exhaust air humidity

Block label	Function	Formula
Ws db	Determine humidity ratio at saturation, wet bulb temperature	Lookup table
xws'	Calculate flow of moles of water at saturation	u[1]*u[2]*.62198

The actual amount of moisture evaporated in the sub-unit is calculated in a block of Fig. 14.4, expanded in Fig. 14.9. The amount of evaporation is determined from the thin layer drying equation, calculated from the values derived from input 3 of Fig. 14.9. Input 2 is the amount of moisture that the air can absorb before it reaches saturation. A switch selects the lower of these two evaporation rates. A further restriction on evaporation rate is the possibility that the latent heat required brings the air below saturation temperature. A second switch determines if this correction is required. The final switch determines if the calculation shows that water is being gained rather than lost. If this is the case the evaporation is set to zero.

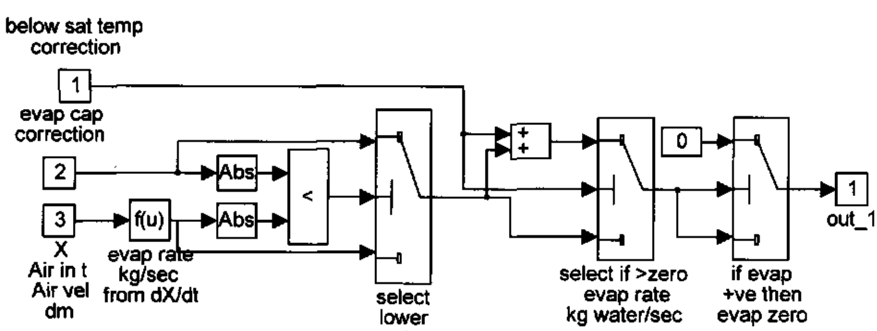

Fig. 14.9 Calculation of evaporation rate from dhool

Block label	Function	Formula
Evap rate kg/sec from dX/dt	Use thin layer drying equation with fluidized bed calibration factor to calculate evaporation allowed from dhool	-(.000284*ratefac*u[3]*(u[2]-45)+.00067)*(u[1])*u[4]

A lookup table in Fig. 14.4 is used to determine the equilibrium moisture content, X_e of the dhool. The difference between this and the actual moisture content X is used in the calculation of evaporation rate.

14.3 Modifications of the continuous model for batch drying

The model may be considerably simplified for batch drying. As a batch fluidized be dryer closely approaches the well-mixed condition, only a single sub-unit is required. The dhool feed rate input is set at zero, and the integrators are initialised with the dry matter mass, the water mass and the starting bed temperature, at the start of the simulation.

14.4 Modifications for exhaust air recycling

Some commercial and experimental continuous fluidized bed dryers recycle the exhaust air from the dry end of the dryer, where very little moisture has been picked up, and supply it to the heaters for an earlier stage. As the same parameters are calculated for the exhaust air as for the inlet air, it is simple to take the exhaust air from one section and feed it to a prior section inlet. Additional air may be required over the exhaust from the later section; calculations on blending the air are then required.

14.5 Modifications for ECP dryer

Another type of dryer commonly used in the tea industry and described above is the Endless Chain Pressure dryer. This is a mix between a cross flow conveyor dryer and a counter current dryer. Because it is a conveyor dryer, the dry matter mass flow is determined by the speed of the conveyor, simplifying the model considerably. A block in Fig. 14.10 represents each deck, or layer of conveyor. Dhool is fed to the top deck, and is then discharged downward layer by layer. The air flows in the opposite direction.

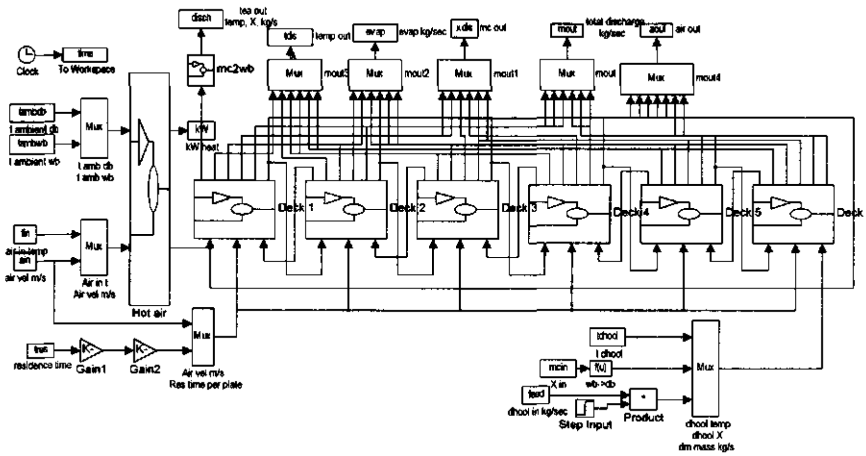

Fig. 14.10 Overall view of ECP dryer

Within each conveyor, the air is more or less uniformly mixed and passes through the conveyor, and the dhool becomes drier as it moves along the conveyor. Thus in each deck or block of the model, the conveyor is divided into eight plates (Fig. 14.11). Air of uniform quality is fed to each plate, while the dhool is passed from one plate to the next. The exhaust air from each plate is averaged together to form the exhaust air from the deck, and fed to the deck above.

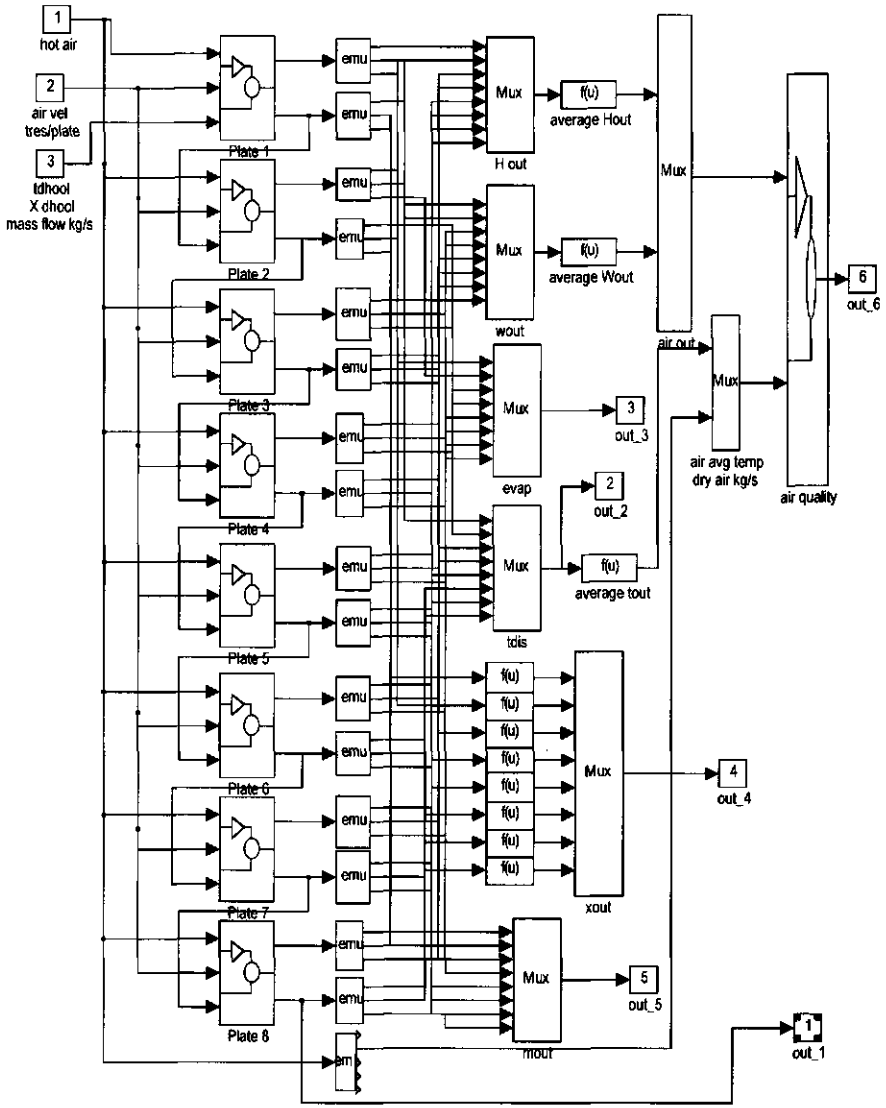

Fig. 14.11 Single deck of ECP dryer

14.6 Routine for calculation of lookup tables

Wsdb = humidity ratio at saturation, dry bulb temperature

Enth = enthalpy

Pws_db = partial pressure of water at saturation, dry bulb temperature

```
function [Wsdb,Enth,Pws_db] = lookup(Tdb,P_atm)

u=273.16+Tdb;                                 % [K]

logpws=(-5800.2206./u+1.3914993-.048640239.*u
+.00004176476.*u.*u-0.000000014452093.*u.*u.*u
+6.5459673.*log(u));

Pws_db=exp(logpws);

P=P_atm*ones(1,length(Pws_db));

Wsdb=0.62198.*Pws_db./(P-Pws_db);            %   [kg   H20/kg
da]

Enth=Tdb+Wsdb.*(2501+1.805.*Tdb);            % [kJ/kg]
```

15 Appendix – Possible improvements to the simulation model

15.1 Introduction

The model developed for fluid bed drying was based on a thin-layer drying model. The fluid bed model was simplified by assuming the whole depth of the bed at any one point to be of uniform moisture content, and by using the air inlet temperature as the effective drying temperature. In order to match the predicted values from the model with measured values from a variety of practical fluid bed dryers, a correction factor on the drying rate of 0.6 was employed.

The need for this factor may be due to bubbling fluidization detracting from efficient mixing of air and material, or may be due to the use of the inlet temperature to drive the drying model. This work aims to establish whether alternatives to the simple use of inlet temperature might provide a more accurate model.

O'Callaghan *et al* (1971) also based their fluid bed simulation model on a thin layer drying model. They assumed vertical plug flow for the airstream, but perfect mixing of the material being dried (grain). In their digital model the layers of grain are interchanged at random after each iteration.

15.2 Method

Because the continuous dryer model employed many stages, some of the modifications envisaged would make the model cumbersome and slow to compute, so the batch fluid bed model was used, employing a single stage only.

One method of calculation was to use the mean of the inlet and exhaust temperatures, in an attempt to obtain an average of the drying conditions.

The second method was to consider the bed to be structured as horizontal layers, each layer approximating better to the thin layer model than the whole bed approach. The modelling system used, Simulink, did not allow the random interchanging of layers at each iteration as used by O'Callaghan *et al.* (1971). Instead, an upward and a downward stream of layers was used, with alternate layers in alternate directions where possible.

This is illustrated schematically in Fig. 15.1 for an eight layer model. A single layer model was used for the control, and compared with an four and an eight layer version. The average residence time in each layer could be programmed, and values of 0.05, 0.5, 5 and 50 seconds were used. Each layer was assumed to be perfectly mixed.

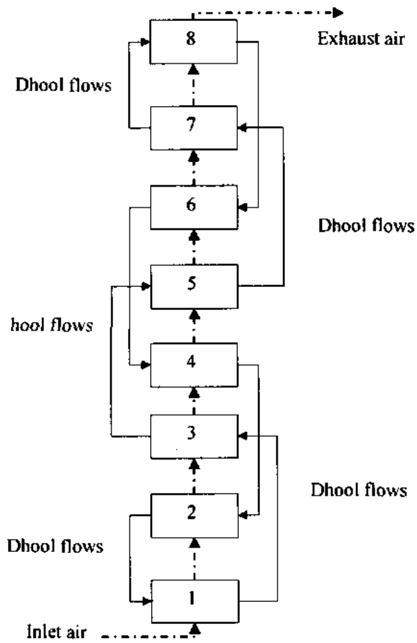

Figure 15.1 Diagram of flow of air and dhool in an eight layer model.

15.3 Results

Practical measurements were compared with the model using the correction factor of 0.6 only, as the actual inlet air flow and temperature readings were used in the simulation model. The other types of model were more complex, and therefore less amenable to this method. The results of this comparison are shown in Fig. 15.2.

To determine which model came closest to the 0.6 factor, the results for each method were combined onto a graph of bed moisture content against time, and another of exhaust air temperature against time. For the purposes of this work a constant inlet temperature of 100°C and a constant inlet air velocity of 1.0 m/s were used. All other values were kept constant for every run. The graph of discharge moistures is shown in Fig. 15.3.

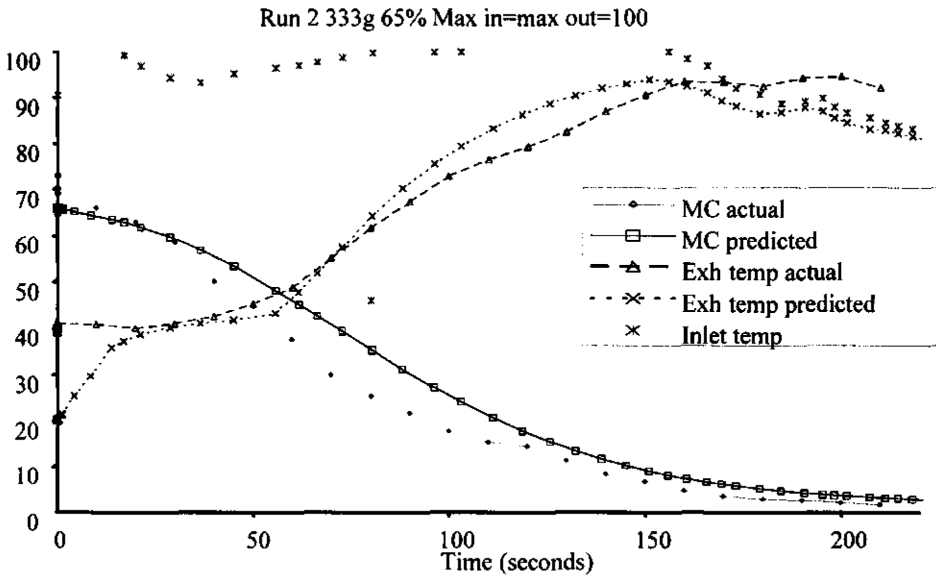

Figure 15.2 Comparison between simple model with correction factor of 0.6 and actual measurement.

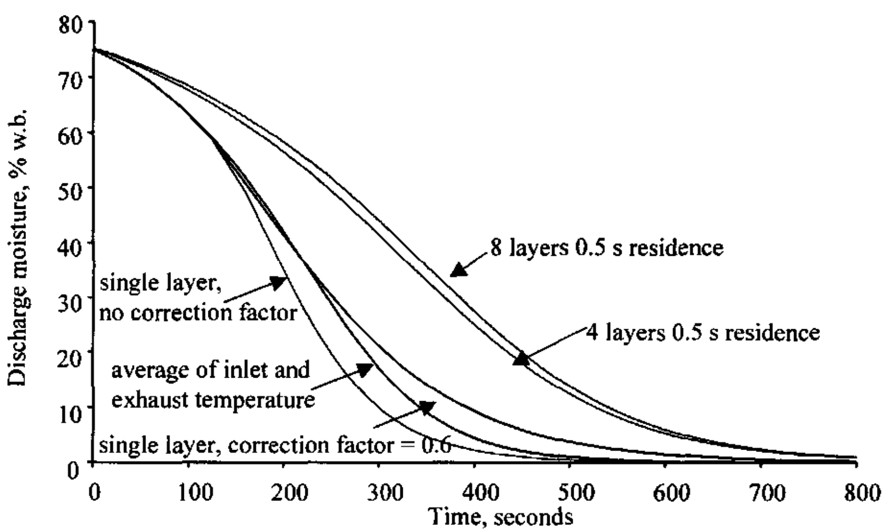

Figure 15.3 Discharge moisture content against time for five different models

The single layer model shows the most rapid drying, while the single layer with correction factor and the single layer with average of inlet and exhaust air slightly less rapid. The slowest drying was observed in the multi-layer models, with very little difference between them. The multi-layer models shown here are for 0.5 seconds residence time; other values of residence time gave slightly higher drying rates but with no consistent pattern. Actual results were found to lie in the region between the single layer with correction factor model and the single layer with averaged inlet and exhaust temperatures.

Now, looking at Fig.15.4 showing exhaust temperatures, the most significant feature of these simulations is the time for which the air is exhausted at saturation, a distinctive feature in actual drying. The multi-layer simulations show no saturation at all after the initial few seconds, because partially dried material will be moving to the top of the bed, and if saturated air encounters this material it will be re-wetted, the air moving away from saturation. If the air is not at saturation then the equilibrium relative humidity of the material will limit the degree of saturation of the exhaust air.

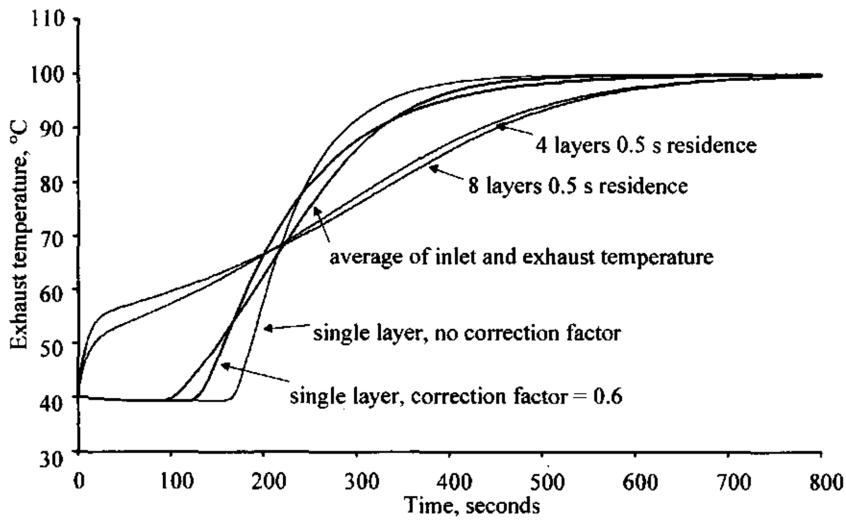

Figure 15.4 Exhaust air temperature against time for five different models

The multi-layer models may be discarded because of the lack of a saturation period. All the single layer models exhibit a significant saturated exhaust period, longest in the model with no correction factor and shortest with the average inlet and exhaust temperature model. Practical results fall closest to the single layer with a correction factor of 0.6, although the average inlet and exhaust model is close.

Because the average inlet and exhaust temperature model has a physical explanation, it might be thought to be preferable. As it was simple to implement on the continuous dryer model, this was tried; the results are shown in Fig.15.5. In the continuous model the inlet and exhaust model grossly underestimates the drying rate, while the model with correction factor produces acceptable results.

The reason for the discrepancies between the continuous and batch models with the average inlet and exhaust temperature model is that, in the batch dryer, the bed shrinks during drying, so narrowing the differences between the inlet and exhaust temperatures. In the continuous dryer, the bed is of constant depth, with a greater difference and therefore a greater impact on drying rate.

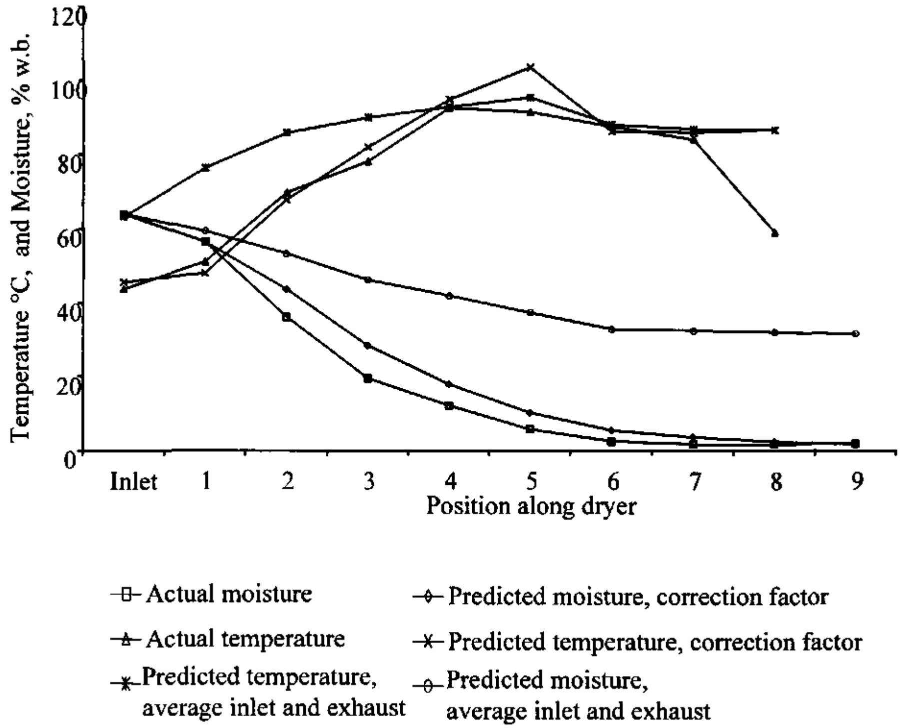

Figure 15.5 Actual and two simulation results from pilot scale continuous dryer.

15.4 Conclusion

Although the correction factor applied to the single layer bed model is the least satisfying on a theoretical basis, in practice it matches the drying behaviour seen in fluid bed dryers best.

This may give some insight into the reason for the factor; it is likely to be due to a fluidization effect rather than a drying effect.

15.5 References

O'Callaghan JR; Menzies DJ; Bailey PH (1971) Digital simulation of agricultural dryer performance. Journal of Agricultural Engineering Research, **16** (3) 223-244

16 Appendix – On-line endpoint determination for batch tea dryers*

16.1 Abstract

A laboratory batch fluid bed dryer was developed for handling small samples of tea for experimental batch manufacture, and this dryer required a means of stopping when drying was complete. A control system was devised which requires only the weight of the sample to be entered into the controller. The system then takes full control, using only an inlet and exhaust temperature measurement. A simulation model was used to explore the operating region of the dryer, and how the various disturbances affected drying time within this operating region. A relationship was found which enabled a simple algorithm to be developed, suitable for implementation on a microcontroller. The method was found to be substantially independent of variables such as sample moisture content and ambient air conditions, as well as inlet temperature, over the range normally experienced. The algorithm was tested in practice and found to give adequate control, substantially better than the manual system used previously.

16.2 Introduction

Batch dryers are commonly used in industry, but less commonly in commercial tea production. Here a batch dryer is used in a laboratory application to prepare samples for further analysis. It is essential to perform this operation consistently in order to guarantee the quality of the laboratory results. At the Tea Research Foundation (Central Africa) a dryer is required for small batches of tea, manufactured for research purposes on the miniature processing system. The batch size can vary from 250 g to 600 g and the batches had to be dried to 3% m.c w.b.. For normal operation, the dryer needs to be controlled to produce a consistent drying curve, such that all samples undergo as near identical treatment as possible. To this end, a control system is required to determine the end of the drying operation and switch the machine off automatically. The existing machine is a tray drier, with manual operation and end of operation determined by time alone, resulting in a moisture content ranging from 2% to 6% w.b.. To emulate commercial production, the dryer needs to dry in a similar way to a continuous fluidized bed dryer, so a batch fluid bed dryer should be used.

Commercially available batch dryers which are used for tea sample drying are limited in power through the constraints of a domestic electrical supply, so either the drying rate or the sample size is limited. They often do not have a vibrated bedplate so

* Submitted to Journal of Agricultural Engineering Research as Temple SJ; van Boxtel AJB "On-line Endpoint Determination for Batch Tea Dryers".

manual agitation is required, at least at the early stages of drying. For reliable experiments, manual intervention must be kept to an absolute minimum.

For non-fluidized bed dryers, it is possible to determine the end point of drying by weighing the material being dried. This gives a measure of moisture loss and if the initial moisture content is known the final moisture content can be calculated directly. Alternatively the moisture content may be inferred from the rate of loss. In a fluid bed dryer the material is suspended in the air, and it is impractical to attempt to measure its weight. Near infrared reflectance moisture measurement is a possible method for end point determination, but costs are prohibitive.

16.3 Methodology

Fig. 16.1 shows the profile of a typical batch drying operation, from the simulation model previously defined by Temple and van Boxtel (1999) which covers continuous and batch drying operations. The curve of exhaust temperature indicates the progress of drying.

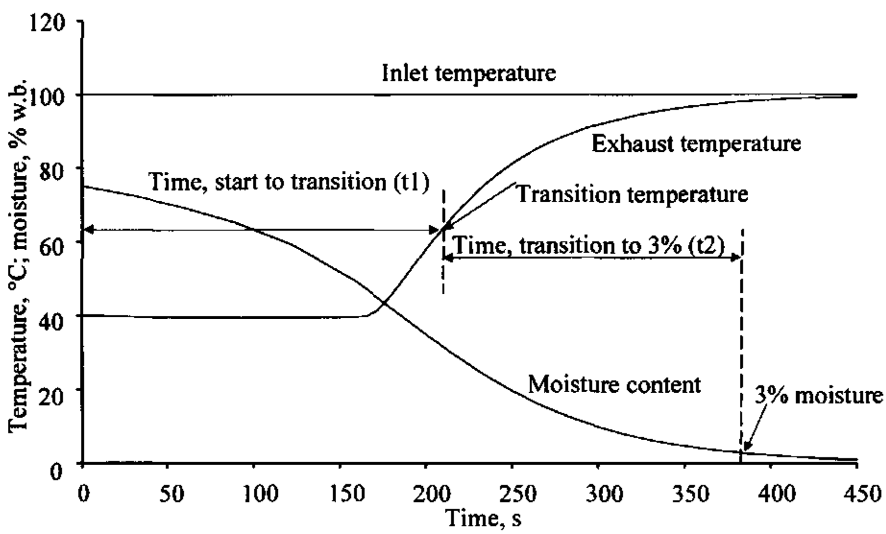

Fig. 16.1 Example of simulated batch drying.

At the start of the run, the exhaust is close to saturation so this temperature value is not useful, and at the end the temperature differential between inlet and exhaust is small, so it is not easy to derive control information at this point. Information must be gained from the temperature transient. There should be a transition temperature during a drying run, such that the time from the start of the run to the instant of reaching the transition temperature (t1) can be expressed as a function of the time from the transition temperature to reaching the end point of 3% moisture (t2). For accuracy of measurement, the temperature should occur when the rate of change of temperature is greatest, normally between 50 and 80°C as in Fig. 16.1. The objective of this work is to identify a transition temperature and a corresponding ratio of t1:t2, so that the end point of the drying cycle can be identified in advance during the drying operation.

The simulation model (Temple and van Boxtel 1999) used is written in the Matlab programming language using Simulink graphical modelling software. It uses a set of differential equations to model the water, dry matter and enthalpy balances in a dryer. The batch dryer model is a special case of the continuous fluid bed dryer model, with no inputs and no outputs. The starting load for the batch is used to initiate the integrators. The model has been validated by independent experiments using the apparatus for which this control system is intended.

16.4 Apparatus

The equipment (Fig. 16.2) was based on the dryer used for validation of the dryer model (Temple and van Boxtel 1999).

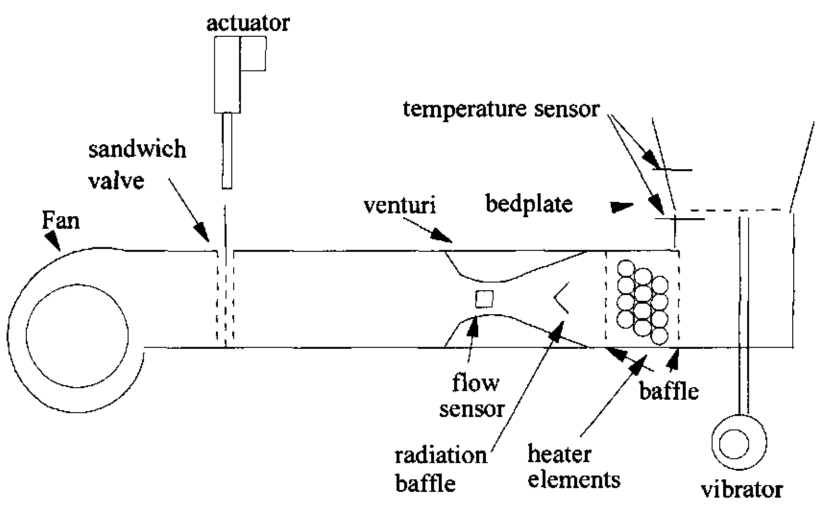

Fig. 16.2 Schematic diagram of batch dryer

The bed area was 0.0576 m^2, and used a perforated metal bedplate vibrated at an amplitude of approximately 1 mm at a frequency of about 10 Hz. For a load of 600 g of dhool of 70% moisture content, this produces an initial bed loading of 10.4 kg/m^2 and a loading at the end of the run of 3.2 kg/m^2.

The system is operated by a microcontroller, which has analogue inputs from the inlet temperature sensor, the exhaust temperature sensor and the airflow sensor†. There is a push button to start a drying run, and a second button to abort a run, or if the dryer is off, to run the fan for a short period for bedplate cleaning. The microcontroller is capable of integer arithmetic only; if more complex functions are required the most effective method of programming is the use of a look-up table.

16.5 Development of the method

A batch file was written to run the simulation model with combinations of different loads, different dhool moisture contents, different inlet temperature settings, different ambient wet and dry bulb temperatures, to cover the full range of conditions to be expected. This resulted in over two thousand runs of the model. The batch file collated the values of the time when the exhaust temperature crossed a given threshold value, such as 60°C, and the time at which 3% moisture was achieved. Fig.16.3 shows that, despite some scatter, the values segregated into groups according to the load of dhool, despite the variation in ambient conditions, inlet temperature, airflow and dhool moisture. Other studies with the model demonstrated that, for a continuous dryer, the feed moisture content had much less effect on performance than feed rate.

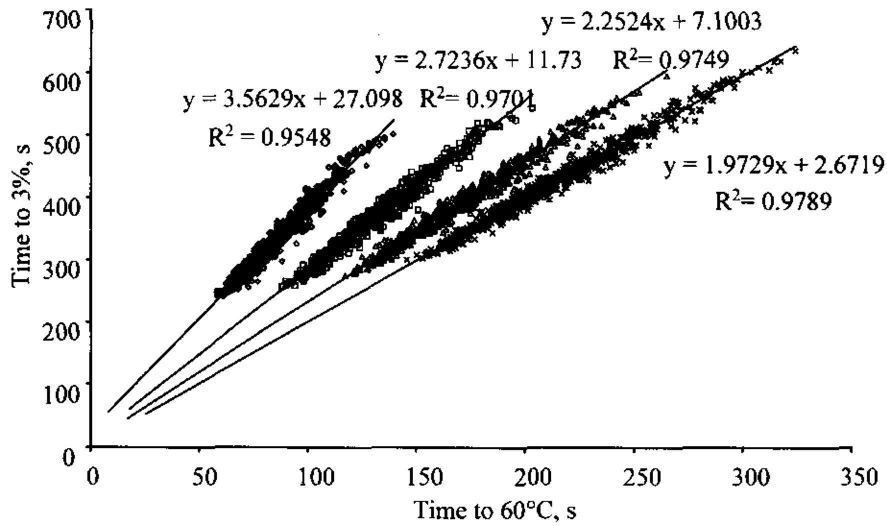

Fig. 16.3 Relationship between time to 60°C exhaust temperature (t1) and time to 3% moisture (t1 + t2). ***Load:- ◊300g (5.2 kg/m²); □400g (6.9 kg/m²); Δ500g (8.7 kg/m²); × 600g (10.4 kg/m²).***

† Control system hardware based on equipment described in :- 17 Appendix – Data logging systems

It is clear from the relationship that, given the starting load, it is possible to determine the time to the end point of drying, irrespective of other variables.

The microcontroller used for this system would use a too large proportion of its resources if floating-point calculations were used, so a simpler formulation is required. Instead of using a fixed temperature, it would be better to determine a temperature at which the time to 3% is an integer function of the time to reach that transition temperature, i.e. either t1/t2 or t2/t1 is an integer. From the slopes of the lines in Fig. 16.3, at 60°C transition, the values are close to 2 (i.e. t1=t2, so the slope of t1 vs. (t1+t2) is 2) (range of 1.9 to 3.6), so the objective was to determine the temperature at which the value is exactly 2 for each load. To this end, a graph was plotted for each load over the range of transition temperatures evaluated in the modelling work. The result for a load of 500 g is shown in Fig. 16.4. Note that the y-axis in this graph now shows t2, the time from the transition temperature to the end, rather than the start to the end as used in Fig. 16.3. This results in slopes close to 1, rather than 2. Examination of the regression data in Fig. 16.4 shows that there is a clear relationship between slope and transition temperature. It is also apparent that the least scatter (greatest R^2) occurs close a slope of 1, and that at the highest temperature the points are segregating into two groups.

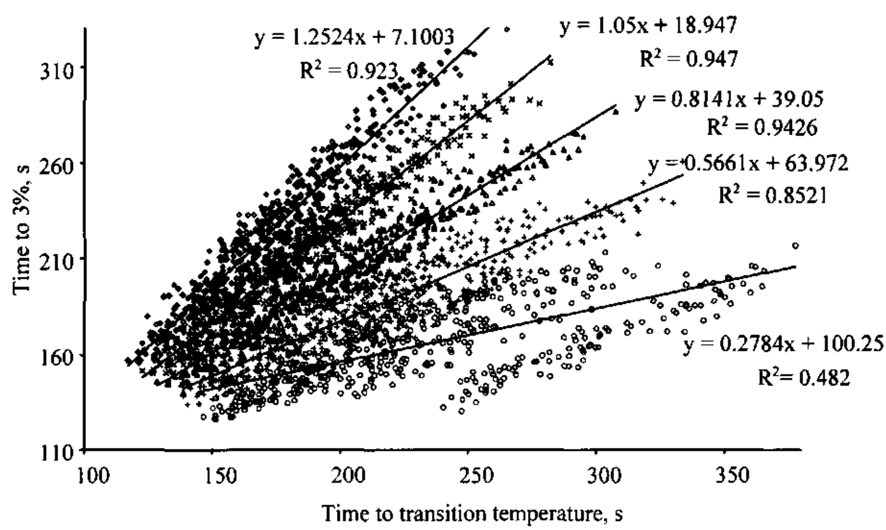

Fig. 16.4 Relationship between time to transition temperature t1 and time from transition temperature to 3%, t2, for various transition temperatures and a load of 500 g. ***Transition temperatures:- ◊ 60 °C; × 65 °C; Δ 70 °C; + 75 °C; ° 80 °C.***

If all the regression lines had intersected at zero, then the task would have been simpler. Unfortunately they did not even have a common point of intersection, so a solution could be to find a simple ratio of t1:t2, then determine the offset or intercept. Taking the slopes of all the regression lines in Fig. 16.4, from a series of graphs for all values of load, allows the plotting of slope against transition temperature for each load.

This produces Fig. 16.5, which plots the slope of the regression line against transition temperature. From this, a value can be read off against a slope (y-axis) value of 1, giving the transition temperature at which a slope of 1 occurs. This is not yet the value required for the control system, because in Fig. 16.4 there was an offset value as well as a slope.

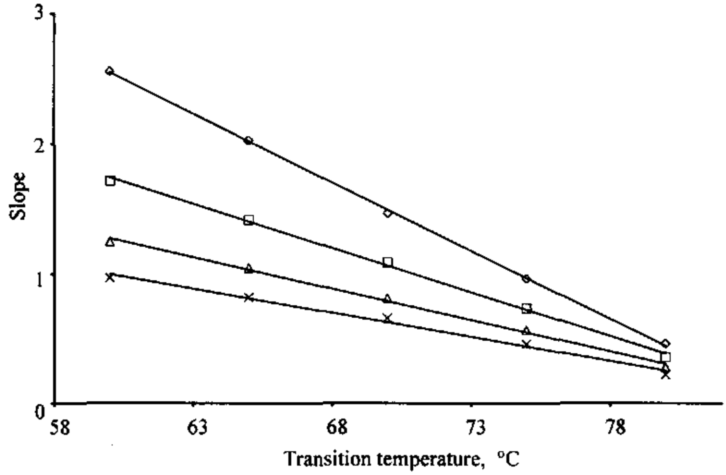

Fig. 16.5 Graph of slope of t2/t1 against transition temperature. ***Load:- ◊ 300g; □ 400g; Δ 500g; × 600g.***

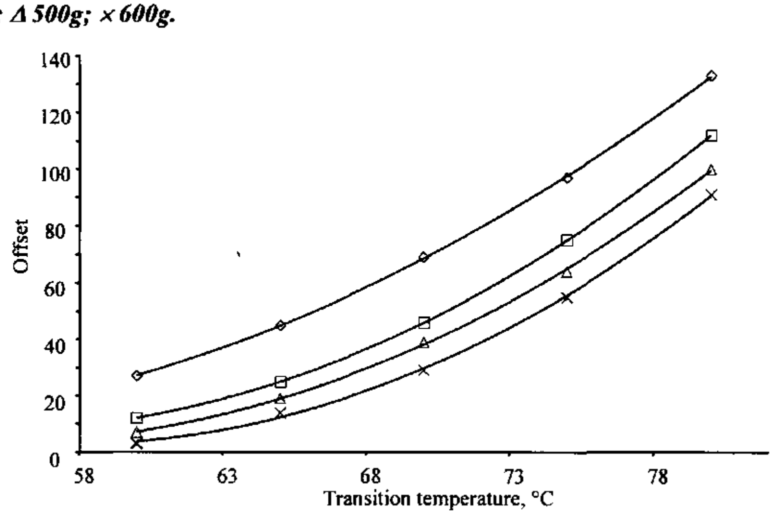

Fig. 16.6 Graph of intercept of t2/t1 against transition temperature. ***Load:- ◊ 300g; □ 400g; Δ 500g; × 600g.***

A graph of these offset or intercept values against transition temperatures (Fig. 16.6) shows that the relationship is no longer linear, and a polynomial has been fitted. From this graph, a value of offset can be read off, using the transition temperature for a unity slope from Fig. 16.5. This procedure may be shown more clearly in Fig. 16.7, combining the slope curve from Fig. 16.5 and the offset curve Fig. 16.6 for a load of 400 g only. Here Line 1 is drawn at a slope value of 1. Line 2 is drawn from where Line 1 intercepts the slope line down to the x-axis, where the transition temperature is read off (71°C). Then Line 3 is drawn from the intercept of Line 3 and the offset curve to the right hand y-axis, to read off the value of offset of 51 seconds.

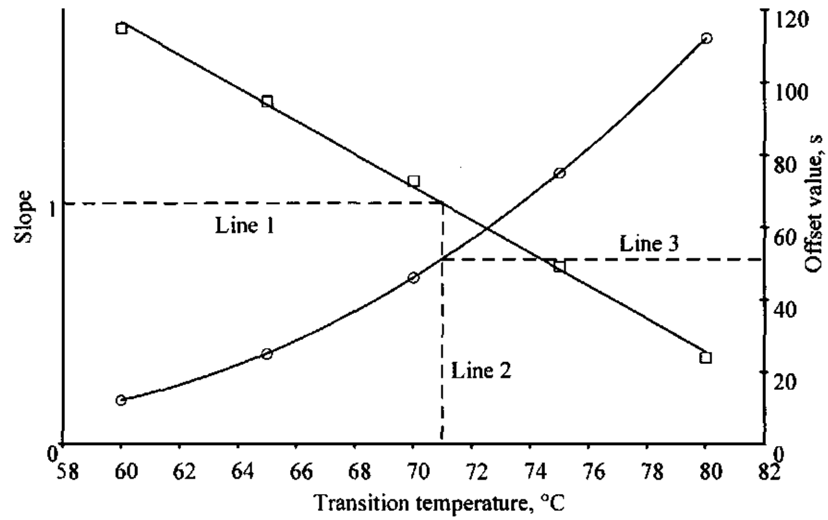

Fig. 16.7 Procedure for obtaining transition temperature and offset for a load of 400 g.

Using this procedure for each value of load produces the data in Table 16.1. For example, on a load of 500 g, the time from reaching 66°C to the end of the run (3%) is the time from the start up to the time of reaching 66°C (t1) plus 22 seconds (t2=t1+22). This is extremely easy to implement on a microcontroller. While the temperature is below 66°, a register is incremented every second; on reaching 66°, the value in the same register is decremented every second until it reaches zero. At this point, the register is loaded with the offset value (22) and again decremented every second until reaching zero. This is then the end of the run and the tea should be at 3% moisture.

To obtain intermediate values, the values determined from Fig. 16.5 and Fig. 16.6 were plotted, resulting in Fig. 16.8, where a polynomial fit is shown. Intermediate values are taken from this graph and are also shown in Table 16.1.

Table 16.1 Parameters for control: values of transition temperature and offset giving t1=t2 for various loads.

Load, g	Transition temperature °C	Offset, s
600	60	4
550	63	10
500	66	22
450	69	35
400	71	52
350	73	73
300	75	98

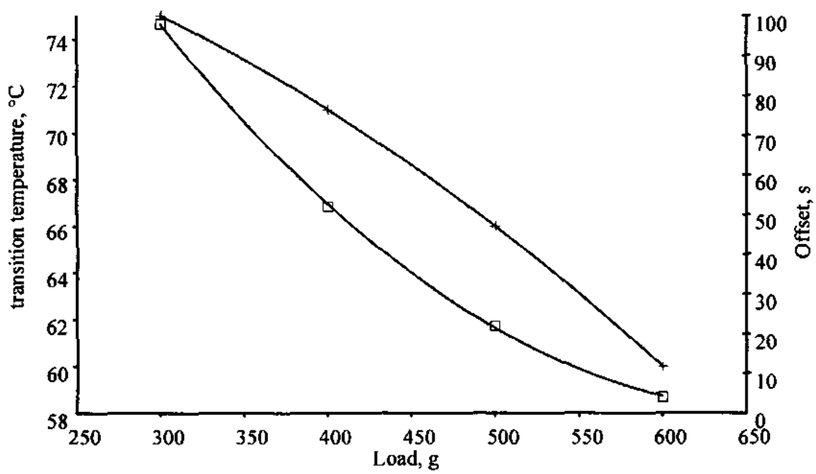

Fig. 16.8 Values for transition temperature and offset to give unity slope (t1=t2), plotted against load. + ***transition; □ offset.***

This algorithm was programmed into the control system, with a front panel switch to select the load in 50 g steps as shown in Table 16.1. A series of runs was carried out at varying loads, with a fixed inlet temperature but with all other conditions uncontrolled and the dhool sample taken from the normal run of production.

16.6 Results

The results gave a mean moisture content of 3.69%, with a standard deviation of +/-0.70 over 13 runs. The variation of +/-0.70 and deviation of 0.69% from the desired value are consequence of clustering all cases to one general solution. However, the result is a far better standard of accuracy than any manual system can maintain, and is very close to the level of accuracy of the near infrared moisture metering system.

Some fine tuning to reduce the mean to 3.0% would give optimal performance. This could be done quite simply by having a control set by the supervisor, not the operator, or by programming a different value into the microcontroller program, which adds or subtracts a small offset to the transition temperature, and possibly a second control for the offset. Increasing the transition temperature, or increasing the offset, will reduce the final moisture content.

16.7 Conclusion

The endpoint of drying for batch dryer units can be determined from the transient temperature. For microcontroller units a simple relation must be used because of limited computing resources. From simulations such a simple relation was derived for different bed loads with the temperature that will be achieved half way through the drying period. This outcome can easily be implemented in a microcontroller to stop the dryer equipment automatically. Experiments showed that the accuracy of the final moisture content was improved by a reduction of the variation in moisture content to much less than that of the traditional manual procedure. Implementation in the microcontroller was simple and in its use only the mass of bed load must be measured and set on the controller, irrespective of changes in other variables over the normally encountered range. Accuracy can be improved by relative simple tuning methods

It might be possible to determine the load automatically, by measuring the pressure required to maintain fluidization, but this would require some sort of detector to control the airflow to ensure that a consistent degree of fluidization is maintained.

16.8 Acknowledgements

This study was partly financed by European Union Stabex funds provided to TRF(CA) for a project on Automation of Tea Processing.

16.9 References

Temple SJ; van Boxtel AJB (1999) Modelling of fluidized-bed drying of black tea. Journal of Agricultural Engineering Research, 74(2), 203-212

17 Appendix – Data logging systems*

Until recently, all measurements and data management in tea processing were made manually, with the potential for mistakes and omissions. A data logging system initially designed for research purposes was developed into a new system that could perform tea factory data logging economically, using computers already used in the factory for financial calculations.

The system is called SLOGGER, a contraction of Serial LOGGER, as it consists of microprocessor based satellite units connected into a network by RS485 serial communication wiring. The standard unit (see Fig. 17.1) can handle up to eight analogue inputs, either voltage or thermocouple signals. The current value of the eight signals going into each unit is shown on a liquid crystal display on the unit.

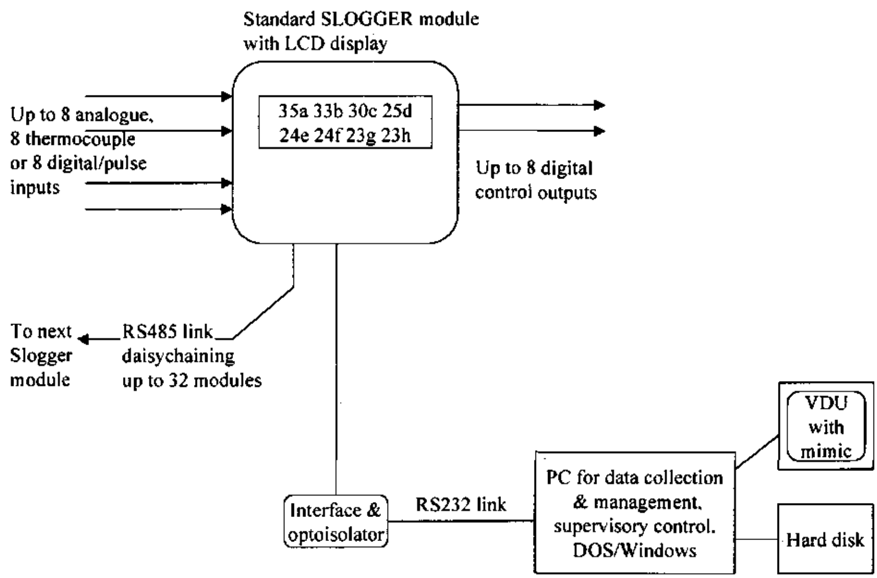

Fig. 17.1 Schematic of a simple SLOGGER system.

As well as the standard module, alternative modules are available to monitor pulse inputs, to display values from another module in graphical form (8 channel bar graph), and to convert a shaft speed signal into a fermenting time.

* This forms part of a paper published as Temple, S.J., Tambala, S.T. and van Boxtel, A.J.B. Monitoring and control of fluid bed drying of tea. Control Engineering Practice (2000) 8(2) 165-173.

Each unit is able to work as a stand-alone device, but full utility is gained from the system when it is connected to a computer. Software is available to run under MS-DOS, carrying out the data logging in the background while the user executes other DOS programs. Alternatively, a Windows program may be used. Both sets of software collect data to disk file, and can display the data as a graph or a table. The Windows software is also able to display selected variables on a mimic diagram.

The system can handle up to 31 modules, potentially 248 data channels. The standard analogue unit is designed with control functions in mind, and an eight way digital output connector is an optional fitting. This can drive relays, and has been used for airflow control and a simplified PD controller operating heater units. It has also been used for the sequencing and control of a batch fluid-bed dryer and data logging from the thin-layer test rig.

Basic components for the system were assembled in Malawi in the configurations required for specific factory installations. The microcontrollers are programmed with the code required for these installations; as one-time programmable chips are used, a new device must be used to upgrade the firmware but the cost of the devices is low. Erasable chips were used during development. Systems have been installed in two-thirds of the tea factories in Malawi as well as for research applications within the Tea Research Foundation (Central Africa).

18 Appendix – Psychrometric relations

The psychrometric equations for determination of air properties were taken from ASHRAE (1981) and CIBSE (1975).

Nomenclature and abbreviations

A value concerning the current air state is shown as "t", the value of the same variable at saturation is shown as "t*". Celsius values for temperature are shown as "t" and absolute (Kelvin) values shown as "T". R is the universal gas constant 8314.41 J/(kg mol.K)

Atmospheric pressure at altitude

$$P_a = P_{sl}.e^{\frac{-1.2 \times 9.81 \times a}{1000.P_{sl}}}$$

where P_a and P_{sl} are pressure at altitude and sea level respectively, kPa, .

Source: CIBSE Guide Section C1/2

Saturation pressure at specified temperature P_{ws}

$$\ln(p_{ws}) = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln(T)$$

for saturation over liquid water in the temperature range 0-200°C where pws is saturation pressure, Pa, T is absolute temperature, °K = °C+273.1, C8= -5.8002206E3, C9=1.3914993, C10= -4.8640239E-2, C11=4.1764768E-5, C12= -1.4452093E-8, C13=6.5459673.

Source: ASHRAE equation 4.

Humidity ratio at saturation W_s

The ratio of the mass of water vapour to the mass of dry air in the sample, calculated as a mole fraction.

$$W_s = 0.62198\frac{p_w}{p - p_w}$$

where 0.62198 is the ratio of molecular masses (18.01528/28.9645), p_w is the partial pressure of water vapour and p is the total pressure of gas.

This is calculated for both ambient conditions and saturation at the wet bulb temperature using the saturated pressures at dry bulb and wet bulb temperatures respectively.

Source: ASHRAE equation 20

Humidity ratio of moist air (dryer input air) W

$$W = \frac{(2501 - 2.381t^*)W_s - (t - t^*)}{2501 + 1.805t - 4.186t^*}$$

Source: ASHRAE equation 33

Degree of saturation μ

The ratio of air humidity ratio W to the humidity ratio W_s at the same temperature and pressure.

$$\mu = \frac{W}{W_s}$$

where $W_s = 0.62198 \frac{p_{ws}}{p - p_{ws}}$

Source: ASHRAE equation 21

Relative humidity ϕ

This is calculated as the ratio of the partial pressure of water vapour present to the partial pressure at saturation.

$$\phi = \frac{p_w}{p_{ws}}$$

Using the value for degree of saturation above we can use the relation

$$\phi = \frac{\mu}{1 - (1 - \mu)(p_{ws}/p)}$$

Degree of saturation and relative humidity are both zero at dry air conditions and both unity at saturation, but differ at values between, and more so at higher temperatures.

Source: ASHRAE equations 22 and 23.

Volume of moist air v

This is expressed in terms of a unit mass of dry air.

$$v = \frac{RT(1+1.6078W)}{28.9645p}$$

Source: ASHRAE equation 26

Enthalpy of moist air h

This is the sum of the enthalpies of the components of the mixture.

$$h = t + W(2501 + 1.805t)$$

where t is the dry bulb temperature and enthalpy is in units of kJ/kg.

Source: ASHRAE equation 30

Water vapour partial pressure p_w

$$p_w = \frac{pW}{(0.62198 + W)}$$

Source: ASHRAE equation 34

Dewpoint temperature

The dewpoint temperature can be calculated from the water vapour partial pressure using the following equation which is valid for the temperature range 0-93°C.

$$t_d = a + b\alpha + c\alpha^2 + d\alpha^3 + e(p_w)^{0.1984}$$

where t_d is dewpoint temperature, °C, α is log of partial water vapour pressure, kPa, a=6.54, b=14.526, c=0.7387, d=0.09486, e=0.4569

Source: ASHRAE equation 35

References

ASHRAE (1981) Handbook - Chapter 6 Psychrometrics. American Society Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, USA

CIBSE (1975) Guide Section C1 & 2 Properties of Humid air, water and steam. Chartered Institution of Building Services Engineers, London

Curriculum Vitae

Stephen Temple was born in Norfolk, England in 1949 into a farming family. Educated at Oundle School, his main hobby there was amateur rocketry, and building control panels for the test firing system. A first degree in Agriculture with Engineering specialisation at the University of Reading was followed by a Masters Degree in Agricultural Engineering from the University of Newcastle upon Tyne.

After almost two years working as a Scientific Officer and Higher Scientific Officer at the Scottish Institute of Agricultural Engineering, he moved to Malawi as Lecturer in Agricultural Engineering at Bunda College, University of Malawi. After two years, there was a break for a year at the family farm where a new farm workshop was set up, then back to Bunda College. The advent of micro-computers and low-cost electronics revived the interest in measurement and control, this time for tractor performance monitoring. Instrumentation of a tobacco barn for a joint project with one of the students and the Tobacco Research Authority led on to employment by the UNDP/World Bank Tobacco Industry Energy Efficiency Project. Here a data-logging computer was designed, and 30 examples built, for monitoring conditions during tobacco curing. The project as a whole managed to bring down the national average fuel consumption (mostly of indigenous hardwood) from 42 m^3/tonne to 22 m^3/tonne over four years.

From there, it was marriage and a move to the south of Malawi, at the Tea Research Foundation (Central Africa) where a new Manufacturing Research Facility was under construction. As well as developing data logging hardware and software, installation, commissioning and modification of the factory equipment was required. Developments from the research data logging system were systems for commercial tea factories, and controllers for the miniature processing equipment which was designed and built in-house.

This work led into the project which developed into this thesis. While these studies were taking place, my wife Catherine was working in parallel on her PhD studies on the "Thearubigins of Black Tea". Her doctorate was awarded in December 1999.

Since leaving Malawi in 1998, he has been based at the family farm in Norfolk. As well as the normal farming activities, the business is looking for opportunities to diversify into instrumentation and control for agriculture.