PHYSICALLY BASED MODELLING AND OPTIMAL OPERATION FOR PRODUCT DRYING DURING POST-HARVEST PROCESSING

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Abstract

The development of new procedures for crop production and post-harvest processing requires models. Models based on physical backgrounds are most useful for this purpose because of their extrapolation potential. An optimal procedure is developed for alfalfa drying using a physical model. The model considers the differences in drying behaviour between stems and leaves of alfalfa, the heat and mass balances of the drying air and a model for a solar energy system. The complete model is used to calculate the dynamic optimal operation for alfalfa drying in a thin layer. The results show that most of the operation time the air flow rate is at a minimum value, so during day time the solar energy is maximally utilized while during night time the costs of additional heating are minimized.
Key-words: Dynamic optimization, drying, physical model, alfalfa

1. Introduction

During the last decades the role of control and decision support systems for production control has increased. For these systems it is essential to have a model of the production process. The large family of models for production control can be characterized in different ways. One way is to make distinction between a class of white models (physical or first-principles models) and a class of black-box models (transfer models, neural nets and fuzzy models). The applicability and suitability of these models depends on the purpose and the situation where the models will be used. For existing systems (existing crop production and processing methods) and the design of traditional regulators black-box models are suitable. For different applications the parameters in the models can be estimated so that the model fits well to existing data and in the future the model can be used for prediction of the considered system. However, in a changing agricultural climate where life-cycles of products lower and with an increasing need for new crops the models require a potential for extrapolation to go beyond the expected and beyond traditional solutions. For that purpose the usability of the black-box models is limited and white models are preferred.

Process optimization is one of the most important methods to advance the actual state of available operation methods. Mostly the momentary values of an objective function are being optimized. However for batch processing of products more benefit can be obtained by using dynamic optimization methods. These methods yield strategies where the operation variables are being varied during the time. Although the principle of a dynamic optimal operation is known for a number of the decades industrial use is still limited due to the computational complexity. Nowadays, with increasing computer capacity these limitations are passing. In this paper an illustration of the development of a dynamic operation for realizing optimal operational objectives is presented on a case study for alfalfa drying. In this study a physical model was used. A specific complication in the case study was the difference in the drying behaviour between the stems and the leaves of alfalfa.

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2. Drying of alfalfa

2.1. Background

With decreasing water concentration the leaves become more and more vulnerable for mechanical handling to enhance drying of the stems (tedding and raking) and for gathering. These operations are not possible for low water concentration of the leaves without significant product loss. Therefore field drying of alfalfa is relatively short and is followed by artificial drying of either baled or unbaled form.

During artificial drying of alfalfa complications arise because (just as in several other agricultural products) stems and leaves have different drying characteristics. The water concentration of the leaves falls faster than that of the stems but it has been observed that during break periods of drying the water concentration of the stems still decreases while that of the leaves increases (Imre et al, 1983). That means that during the break the water concentration of the components equalizes. From the moisture equalization in the breaks it may be expected that intermittent drying is beneficial to avoid large differences between the water concentrations of the stems and the leaves (Imre et al. 1983). Namely in the breaks the drying of the stems proceeds while the leaves are being rewetted which finally yields a homogeneous product. Intermittent drying can be of special interest for the application of solar energy, as a cheap energy is available during day time and a break can be applied in the night.

As indicated from the equalization of water concentration it is expected that beneficial results can be obtained by intermittent drying using solar energy, and calculation results indeed show progress. But it is not proven that real optimal results are achieved. To estimate the true optimal operation a physical model of stems and leaves drying has to be combined with optimization methods for dynamic processes and using an objective function.

2.2. Drying system configuration

A system configuration for drying is schematically given in Fig. 1. The fan transports the air through the solar energy system, heater and drying bed. The ambient air is heated up by the solar energy system till T_{sol}. The solar radiation, the ambient air temperature and air humidity vary during the day and as a consequence T_{sol} is a function of day time and is furthermore a function of the air flow rate. The heater is used for additional heating of the air. The necessary conditions for drying are the required input temperature for the dryer (T_h) and the air flow rate. These variables are used as optimization variables.

The dryer in this study concerned was a packed bed of material. The air was distributed equally over the cross sectional area of the dryer before entering the dryer. Compared to the drying time (days) the time constants of the heater, fan and solar system (seconds and minutes) are relatively fast. As a consequence in the modelling steps steady-state equations for these installations were used.

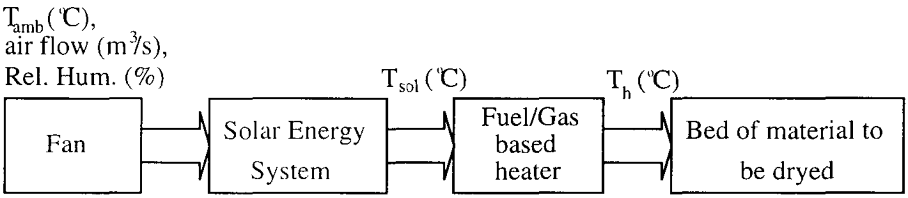

Figure 1 - Schematic presentation of the drying system

2.3. A physical model for a drying of unbaled alfalfa

In order to follow entirely the moisture change in the components and finally to determine the moisture and temperature distribution along the height of a alfalfa in a fix-bed layout, separate models for the drying of the leaf and stem components of alfalfa were used including their particular sorption isotherms. These models were combined with air mass and enthalpy balance equations for the fixed bed. The governing equations are as follows:

The heat balance of the leaves in revise form is

$$c_L \rho_L \frac{\partial T_L}{\partial t} = a_L [\alpha_L (T_a - T_L) - rN_L].$$

The mass balance of the leaves is

$$\frac{\partial X_L}{\partial t} = -\beta_L a_L (X_L - X_{eL}).$$

The drying rate of the leaves is

$$N_L = \beta_L \rho_L (X_L - X_{eL}).$$

The heat balance of the stems in revise form is

$$c_S \rho_S \frac{\partial T_S}{\partial t} = a_S [\alpha_S (T_a - T_S) - rN_S].$$

The mass balance of the stems is

$$\frac{\partial X_S}{\partial t} = -\beta_S a_S (X_S - X_{eS}).$$

The drying rate of stems is

$$N_S = \beta_S \rho_S (X_S - X_{eS}).$$

The heat balance of the air is

$$c_{pa} \rho_a \varepsilon \frac{\partial T_a}{\partial t} = -a_L (N_L c_{pw} + \alpha_L)(T_a - T_L) - a_S (N_S c_{pw} + \alpha_S)(T_a - T_S) - c_{pa} \Phi_a \frac{\partial T_a}{\partial z}.$$

The mass balance of the air is

$$\rho_a \varepsilon \frac{\partial X_a}{\partial t} = (a_L N_L + a_S N_S) - \Phi_a \frac{\partial X_a}{\partial z}.$$

To the solution of the model we can use the above partial differential equation system consisting of six equations referring to the six unknown variables X_L, X_S, X_a, T_L, T_S and T_a including the parameters and the additional sorption isotherms X_{eL}, X_{eS} (Imre et al, 1983; Farkas and van Boxtel, 1994), as well. If both the sorption and desorption isotherms of the components are available then the model can be used for the calculation of the rewetting phase during the course of the drying. During the solution the boundary condition of $T_a(z=0)=T_h$ was applied at the entrance of the bed.

Using a block-oriented approach to practically solve the model, a thin layer block can be defined on the basis of space discretization of the governing partial differential equations. The discretization step interacts with the accuracy to be achieved, but at the same time a model with too small discretization steps cannot be easily used for control purposes.

When considering the possibilities for simplifying the model, it is important to retain the physically based concept. In order to avoid numerical complexity, a model reduction procedure was considered and applied to obtain an approximate physical model.

The following steps of the model reductions are carried out:

i) Neglecting the dynamics of temperature of material components

$$\frac{\partial T_L}{\partial t} = 0, \quad \text{and} \quad \frac{\partial T_S}{\partial t} = 0.$$

ii) Additional neglecting the dynamics of the air temperature

$$\frac{\partial T_a}{\partial t} = 0.$$

iii) Additional neglecting the dynamics of the air moisture

$$\frac{\partial X_a}{\partial t} = 0.$$

2.4. A model for the solar energy system

The solar energy system considered was supposed to be placed on the roof of a barn. The 0.1 metre wide space through which the air flows, was formed by an upper glass layer and an underlying black surface of PUR foam insulation. The solar energy model is based on the heat balance. From the equations it was derived that the temperature of the air after passing the solar collector is given by

$$T_{sol} = \frac{cT_{amb} + Q_{rad}}{c}, \quad \text{with} \quad c = \Phi_a \rho_a (c_{pa} + c_{pw} X_a) + A_c \frac{R_1 + R_2}{2R_1 R_2}.$$

2.5. Use of the model

The model described before is a suitable tool for calculation of moisture distribution in different alfalfa components in the complex drying system, which includes also a solar-based energy supply system.

A sensitivity study was carried out in order to determine the optimal size of thickness of an alfalfa layer can be applied during the simulation. A half metre thick fix-bed of alfalfa was considered as an initial parameter. The bed was devided into 1, 3, 9 and 27 layers to keep the comparability for comparison in the middle layer. The "1 layer" represents the total thick bed. On the basis of the given example it was found that 9 layers was sufficient, i.e. $\Delta z = 0.05$ m size of space discretization can be used in drying calculations.

The full-scale physical model is preferably used for design of dryers. In that case it is obvious to know the moisture and temperature distribution along the depth and cross section of the dryer. The main troubles of such a solution could be the long calculation time, the numerical errors and stability in close connection with the time and space discretization applied. Hence, the full-scale physical model cannot be successfully applied for the purpose of drying operation or optimization. For that cases black-box (input/output) models are used primarily. But, after making reliable reductions in the physical model it could yield a still physical model satisfies the requirements for process control, first of all, due to its fast calculation possibilities.

As it was mentioned before three different stages of model reduction were considered in analysing the possibility to reduce the calculation time along with keeping the calculation accuracy in moisture distribution. The study of reduction steps showed that already the step i) i.e. neglecting the dynamics of temperature of material components gives a reasonably good results. The calculation time is about ten times less and the accuracy stayed within 0.5 % compared to the original model.

3. Optimal operations

3.1. Optimization

The alfalfa dryer in this study was a batch process. For batch processes optimality of momentary objectives is not relevant. The final result of the operation is the true objective. That means that the final product must satisfy the specifications and the total yield at the end of the operation must be optimal. These objectives can be realized a *dynamic optimal operation* where the operation variables *change* during the operation (Fig. 2).

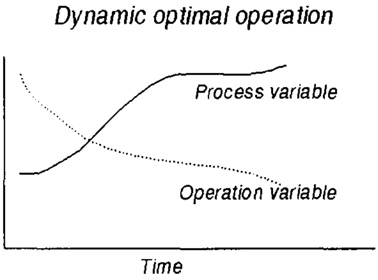

Figure 2 - Schematic representation of the courses of input and process variables for a dynamic optimal operation policy

Dynamic optimal operations satisfy the optimality conditions better than the static optimal operations, but for some applications the difference is not that significant to justify the additional investments for a dynamic optimal operation.

Static optimal operations are calculated by using relatively simple methods as for example hill-climbing methods. In the calculation of a dynamic optimal operation the influences of the values of the operation variables at each moment of the operation are taken into account. Therefore dynamic optimization requires more advanced calculation methods and significantly more computational effort. Standard procedures, as for example the first order-gradient method used in this investigation (Bryson and Ho, 1975).

3.2. Objective function, constraints and input data

The objective function concerned the minimization of operational costs, i.e. the energy costs for fan power and heating

$$J = \int_{t0}^{tf} \{ \frac{\Delta P \Phi_a El}{\eta_f} + \frac{\Phi_a \rho_a c_{pa} (T_h - T_{sol}) Fuel}{\eta_h} \} dt \quad \text{with} \quad \Delta P = aH \frac{\Phi_a^{1.6}}{A_d} \exp(X_{mean}) .$$

Additional constraints were set on the water concentration of stems and leaves at the end of the operation. The water concentration of the stems was prescribed at 0.12 kg water/kg dry matter, while the mean water concentration of steams and leaves was set at 0.15 kg water/kg dry matter (information from industrial dryers). From these constraints, the weight ratio of stems and leaves and the potential for water exchange between the stems and the leaves it was derived that the water concentration of the stems at the end of the drying period should be 0.1928 kg water/kg dry matter.

To illustrate the role of minimum and maximum constraints on the drying conditions the air flow rate was allowed to vary between 0.02 and 1.0 m^3/s and the temperature behind the heater between T_{sol} and 70 °C. These values seemed acceptable for users of drying equipment. For the calculation of optimal operation strategies Dutch long yearly mean values for each hour per month for the air temperature, relative humidity and direct and diffuse solar radiation were used.

4. Results

4.1. Optimal operation

A large number of calculations were performed. To illustrate the outcome the results for two different cases will be discussed. The first case concerns a drying time of 96 hours. The second case which is mentioned in the next section concerns a drying time of 60 hours and different constraints on the final water concentration. This case was used to emphazise the potential use of water exchange between stems and leaves. In both cases drying was started in the evening after alfalfa collection and short field drying.

The optimization results for a 0.05 metre thick layer are given in Fig. 3. In the first 10 hours water transfer from stems and leaves is relatively high and requires gradually decreasing air flow rates above the minimum value (Fig. 3a). After this period the minimum air flow rate satisfies to minimize the costs for energy consumption by the fan and costs for heating.

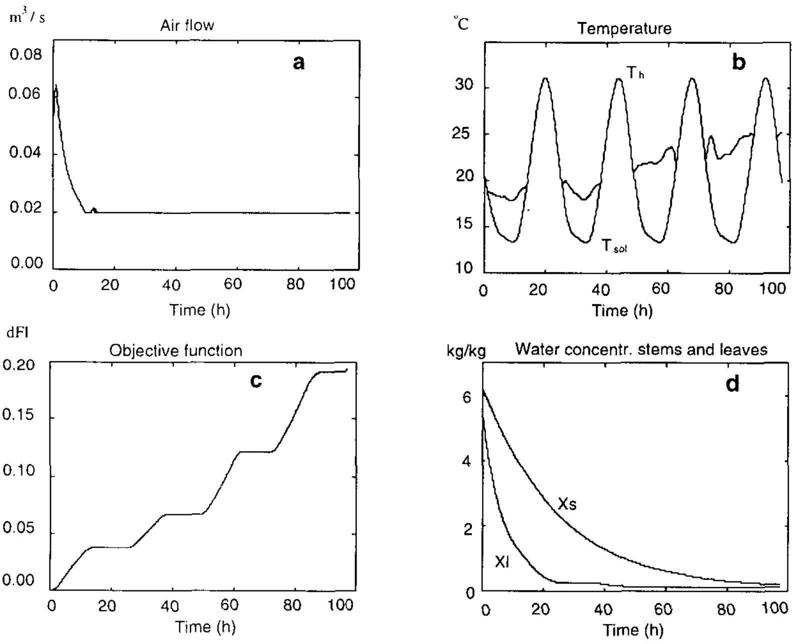

Figure 3 - Optimization results

Because of the low air flow rate, the air is significantly heated in the solar energy system (Fig. 3b). As a consequence the relative humidity is low and the driving force for drying high. Therefore, additional heating is not necessary during day time.

At night additional drying is required. Because of the lower night temperatures the air is heated to realize a better driving force for drying with a lower relative humidity. During the succeeding nights the mean temperature increases from about 19 °C till 25 °C.

Fig. 3c shows that the operational costs are the highest during the night and almost negligible during the day. Fig. 3d presents the water concentrations in stems and leaves. Drying of the leaves is much faster than drying of the stems, but after 40 hours the drying conditions were chosen in such way that the leaves did not dry any more.

4.2. Discussion

The optimization calculations do not result in a intermittent drying procedure, where the equipment is alternating being switched between on and off. In the first period of drying, with the highest values of water transfer, the air flow rate must be above its minimum value and can be set to the minimum value during the rest of the time. Such high values are necessary to avoid a decreased driving force for drying due to an increase of relative humidity.

Moreover, for the applied solar energy system and climate data which vary for every hour, during the day the solar energy must be used in such a way that the highest driving force for drying is realized, and during the nights additional drying is required although on a low level. The results showed that the driving force for drying is most effective controlled (i.e. cheapest) by an increase of the temperature of a small air flow instead of a higher air flow at constant temperature. During succeeding nights the water concentration decreases more and more and hence the driving force for drying lowers. For compensation the temperature in the succeeding nights increases slightly.

Of course with changing parameter values and input data the course of the air flow rate and temperature will change. But a sensitivity analysis showed that the basic idea of the course for the air flow rate and temperature remained the same for other parameter values.

The variation of temperature during the nights (e.g. 60 and 80 hours) are not yet completely understood. Possibly they are results of shortcomings in the applied algorithm. It must be noted that these variations are not crucial for the optimization results. Simulation showed that a smooth course of the temperature at these moments did not affect the results too much.

Consequences of changed constraints on the final values and drying time are presented in Fig. 4 which concerns results for higher prescribed final values of water concentration of stems and leaves (respectively for stems and leaves 0.65 and 0.4 kg water/kg dry matter) and the drying time was reduced to 60 hours. Most remarkable phenomenon for the drying history is that first the leaves are being dried to values below the prescribed values and later process conditions have to be applied which result in rewetting of the leaves while the stems still are being dried. Comparable drying procedures were also suggested for drying of vegetables (information from industrial drying companies).

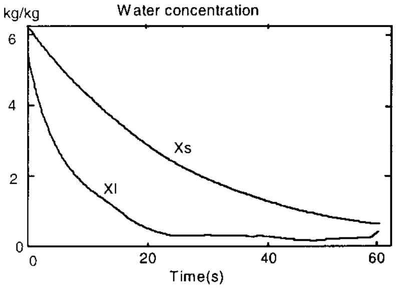

Figure 4 - Drying history of stems and leaves for increased final constrains and final time of 60 hours

5. Conclusions

To work out true optimal operations for batch wise processes physically based models are required. The models should be combined with methods for dynamic optimization. The obtained strategy indicates in which way the operation variables must be varied to realize or approach or approximate optimality. The results are easy to understand, but mostly not as expected on first sight.

Mass and heat balances are good starting-points to build models of production systems. Basic knowledge on transport phenomena, transformation kinetics, general data and physical constants given in handbooks can be used. Models of subsystems can easily be combined to simulate the systems behaviour and the total outcome.

In order to describe the moisture distribution of alfalfa during the drying process a two-component (leaf and stem) physically based model is essential. During the breaks in drying rewetting process in stem components could appear which can be calculated with the knowledge of sorption and desorption isotherms of both components.

The physically based models serve detailed useful information on the moisture and temperature distribution of the drying bed which is very important in the stage of design. However, their solution may cause troubles sometimes like long calculation time, numerical errors and stability problems. The model reduction is a way to get an easily applicable model for operational, optimization and control purposes along with the benefit of keeping the physically based concept.

The utilization of solar energy is useful for alfalfa drying, but for the nights it is essential to provide in additional heating on a low level.

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Symbols

a	Constant; Specific surface area (m^2/m^3)
A_c	Area of solar collector (m^2)
A_d	Cross sectional area of dryer (m^2)
c	Additional variable; Specific heat (J/kg °C)
c_{pa}	Specific heat of air at constant pressure (J/kg °C)
c_{pw}	Specific heat of water at constant pressure (J/kg °C)
El	Electricity costs (dFl/kWh)
Fuel	Fuel costs (dFl/J)
H	Bed height (m)
N	Drying rate (kg/s m^2)
Q_{rad}	Radiation energy (W/m^2)
r	Latent heat (J/K)
R_1	Heat resistance of glass layer (m^2°C/W)
R_2	Heat resistance of PUR insulation layer (m^2°C/W)
t	Time (s)

T_a	Drying air temperature (°C)
T_{amb}	Ambient air temperature (°C)
T_h	Temperature after heater (°C)
T_L	Temperature of leaf (°C)
T_S	Temperature of stem (°C)
T_{sol}	Solar preheated temperature (°C)
X_a	Water concentration in air (kg/kg)
X_L	Moisture content of leaf (kg/kg)
X_S	Moisture content of stem (kg/kg)
X_{mean}	Moisture content of alfalfa (kg/kg)
z	Height (m)
α	Heat transfer coefficient (W/m^{2}K)
β	Mass transfer coefficient (m/s)
ε	Porosity (m^3/m^3)
φ	Relative humidity of air (-)
Φ_a	Air flow rate (m^3/s)
ρ_a	Density of air (kg/m^3)
η_a	Fan efficiency (-)
η_h	Heater efficiency (-)
ΔP	Pressure drop over bed (Pa)

Additional subscripts

a	air	L	leaf
e	equilibrium	S	stem