Energy Efficient Multistage Zeolite Drying

for Heat Sensitive Products

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Preface

This thesis presents the research for my PhD-thesis in the Systems and Control Group and Valorisation of Plant Production Chains Group, department of Agrotechnology and Food Science and A&F of Wageningen University and Research Centre. The research was funded by TPSDP Project Diponegoro University Semarang Indonesia, and the Energy Research Program EOS of the Dutch Ministry of Economics conducted by SenterNovem (project NEOT01005). The topic concerns energy efficient adsorption drying using zeolite for heat sensitive products and was supervised by dr. Ir. A.J.B. van Boxtel, dr. ir. P.V. Bartels, Prof. dr. J.P.M. Sanders and Prof. dr. ir. G. van Straten. To facilitate the research an adsorption dryer was constructed by Ebbens Engineering, zeolite was provided by CECA (Brenttag), C.J. van Asselt and B. Speetjens assisted with the measurement and control system.

The research involves the evaluation of the energy consumption of a conventional dryer, the development of single and multistage adsorber drying systems using zeolite for air dehumidification, the characterization of transport phenomena in zeolite beds and material to be dried by using one and two dimensional models, the evaluation of the energy efficiency for the developed dryer systems, the construction of an experimental dryer and evaluation of the energy performance of this system, the prediction of the dryer performance for a range of operational conditions, and suggestions for the construction of the drying concept for large scale application. The work is given in seven chapters where five chapters are published in or submitted to an international journal. Moreover, other part of the works have been presented at national and international seminars.

Contents

Chapter 1

Reducing Energy Consumption in Drying: a Challenge for Adsorption Drying

1. Energy consumption in drying

Drying is a basic operation in food, pharmaceutical and chemical industry. The operation is important to enhance the preservation properties of agriculture crops and pharmaceutical products, to reduce the costs for transportation, and to increase costumer convenience of food products. An example is milk powder that can be stored for a period longer than a year instead of some weeks[1] and for which the transportation volume is 8-10 times reduced. Nowadays, the importance of powdered food products as for example soups, sauces and dried yeasts is increasing for consumer convenience.

A large part of the total energy usage in industry is spent in drying. For example 70% of total energy spent in the production of wood products, 50% of textile fabrics, 27% of paper, 33% of pulp production is used for drying[2] (see Figure 1.1). In food and pharmaceutical industry the energy consumption for drying is around 15% of the total energy usage in this sector. Energy spent for drying varies between countries and ranges between 15-20% of the total energy consumption in industry.[3]

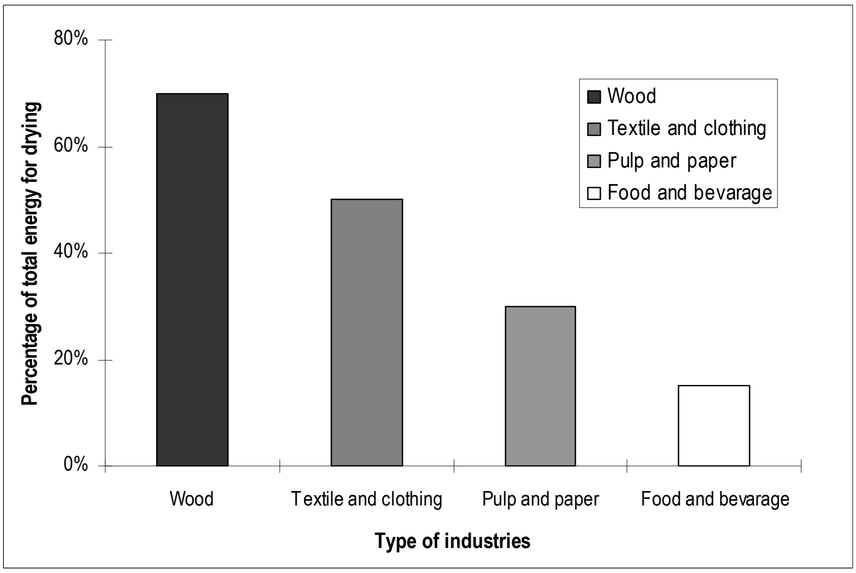

Figure 1.1: Percentage of energy used for drying for several industries

Currently several drying methods are used, ranging from traditional to modern processing: e.g. direct sun drying, convective drying, microwave and infra-red drying, freeze and vacuum drying. Current drying technology is often not efficient in terms of energy consumption and has a high environmental impact due to combustion of fossil fuel or wood as energy source.[4] The sources of fossil fuel are limited, the price of energy increases, the world wide industrial energy usage rises, and increase of greenhouse gas emission becomes a global issue due to climate change; the need for a sustainable industrial development with low capital and running cost especially for energy becomes more and more important. In this context the development of efficient drying methods with low energy consumption is an important issue for research in drying technology.

A large range of drying methods is being applied by small and industrial users. Next consideration is just a limited review on some major drying methods. Direct sun drying is simple and doesn't need fuel fossil for energy generation, but the system needs a large drying area, long drying time (often 3-5 days), high operational cost for labour, and depends highly on the climate. Furthermore, product contamination may occur due to the open air conditions and therefore sun dried food products are not accessible for all markets. Improvement of this drier type has been achieved by using for example a solar tunnel drier equipped with an electric fan to dry chilli.[5] Although, the result showed that the processing time is reduced, it is still rather long (2-3 days).

Convective drying[6] is more attractive than sun drying because of the shorter operational time, low product contamination, lower operational costs, no dependency on the climate, and relative limited space usage. However, the disadvantage of this system is that the product quality can be affected by the operational temperature, and the high energy consumption.

Vacuum and freeze drying systems are operated in the temperature range –20 to –0^{o}C and for pressures in the range of 0.0006 to 0.006 atm.[7,8] These systems are useful for the production of high quality, high value products with minimizing flavour loss and degradation reactions (e.g. protein denaturation, browning and enzymatic reactions [9]). However, Hu et al[7] showed the vacuum freeze- dryer is high energy consumption, investment costs, and long drying time.

Considerable amounts of energy are lost in the off-gas of convective drying systems. The off-gas temperatures are commonly in the range 60-90°C but may even rise till 120°C as reported for spray drying of Roselle extracts[10] and sugar-rich food products. Until now, off-gas flows with these temperatures are hardly recovered for use in other processes. As a result, the energy efficiency of drying is poor. The energy equivalent of about 1.5 kg of steam to remove 1 kg of water (i.e. 65% energy efficiency) is common for spray drying, and for low temperature drying of heat sensitive products (food and medicines) the required amount of energy exceeds 2 kg steam for 1 kg water removal (i.e. below 50% energy efficiency).

The energy efficiency depends on various process characteristics such as evaporation rate, steam consumption, and energy uptake by other processing units. A common definition for energy efficiency is the ratio between the total energy required for evaporating water from the product and the total amount of energy introduced to the system (see equation 1).[2] Table 1.1 presents the energy efficiency for drying compiled from various sources.

$$\eta=\frac{Q_{evap}}{Q_{intr,total}}100\% \qquad (1)$$

Considering the given energy efficiency values it is a challenge to work on the development of innovative dryers with a high drying rate, high energy efficiency, low investment and operational costs, and feasible for low and medium drying temperatures.[7] Innovation and research in drying technology during the last decades resulted in reasonable improvements, but breakthrough solutions with respect to the energy efficiency are scarce. Some authors state that innovation in drying technology tends to reach a saturation level[4] and a further significant reduction in energy consumption seems not feasible. Positive results are obtained in zeolite drying to speed up drying rate and to improve energy efficiency,[14-17] while other new developed drying processes cannot compete with traditional drying method in terms of energy efficiency and operational cost[4].

Table 1.1: comparison of average efficiency for drying in selected dryers

No.	Dryer Type	Energy efficiency (η %)	Steam consumption (kg steam/kg water removal)
1	Cabinet dryer[11]	20-30	3.0-5.0
2	Vacuum-shelf dryer[11]	35-40	2.5-3.0
3	Freeze-dryer[11]	10-20	5.0-10.0
4	Spray dyer [12]	30-60	1.6-3.0
6	Screw conveyor dryer[13]	25-60	1.6-4.0
7	Fluidized bed dryer*	30-70	1.5-3.0

* compiled from various sources and depends on product type

2. Adsorption dryer for medium temperature drying

The main problem in drying is how to improve the drying rate in combination with minimizing energy usage. Straightforward solutions are: reducing humidity of air, increasing air temperature, decreasing air pressure, or combinations of these three. The choice depends on the heat sensitivity of the product to be dried. Increasing the air temperature or reducing air pressure reduces both the relative humidity of air which increases the drying capacity and driving force for drying. However, increasing air temperature leads to quality degradation of heat sensitive products, while reducing the pressure yields increased operational costs and inefficient energy usage.

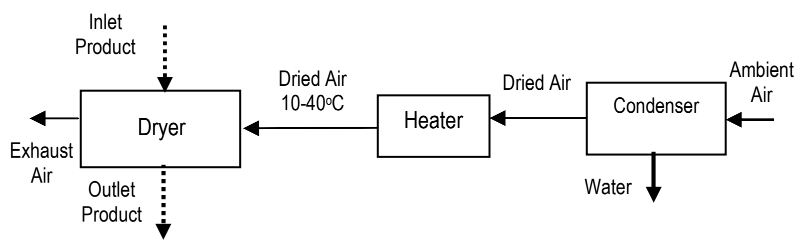

Figure 1.2: A schematic diagram for drying with air dehumidification by condensation. Ambient air is cooled to 0°C and vapor in air condenses. The dehumidified cold air is heated–up to the required dryer temperature and fed to the dryer. In the dryer the dehumidified air dries the product and leaves the drier.

Air dehumidification improves the driving force for drying at the same or lower temperatures, and allows drying at low and medium temperatures and atmospheric pressure. These conditions are suitable for heat sensitive materials such as food and pharmaceutical products.

Figure 1.2 presents a conventional dryer for low temperature drying in which air is dehumidified air by condensation. In a first step air is cooled and the vapor in air condenses. Then the dehumidified air is heated to the drying temperature. In this system energy is used for two functions: 1) cooling and condensation of vapor in air, and 2) for heating dehumidified air to drying conditions[18].This method is energy inefficient. Sosle et al[19] proposed the use of a heat pump in this system. Compared to the conventional dryer using hot air, the quality product is better, but the energy efficiency is lower due to much of energy loss in the condenser. Xu et al[20] proposed a combination of a vacuum freeze dryer and a convective air dryer in two successive stages. This system could be a potential option, since the product quality is maintained. The energy efficiency of 50-60% is only meaningful as an alternative for vacuum freeze dryers.

Air dehumidification by using adsorbents[14-17,21] is an other option to enhance the drying efficiency (see Figure 1.3). With this method, the air is dehumidified by adsorbing vapor while the air temperature increases at the same time due to the release of the adsorption heat. As a result, the dryer inlet air contains more sensible heat for drying which improves the total energy efficiency. However, straightforward application of adsorption dryers using silica, alumina or zeolite as adsorbent for food and medicinal products is not attractive. By taking into account the energy for standard regeneration of adsorbents, energy savings compared to a conventional dryer are estimated to be around 10-15%. In an alternative approach, the zeolite is regenerated with superheated steam. The benefit of this system is that the energy in the off-gas of the regeneration unit is nearly fully recovered and can be used for other operations.[17]

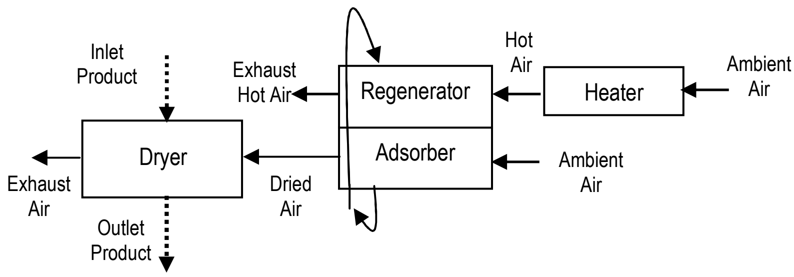

Figure 1.3: A schematic diagram of an adsorption dryer in which air is dehumidified by an adsorbent in a rotating wheel. Ambient air passes the adsorber zone of a rotating wheel where air is dehumidified and where the air temperature increases. Then, the dehumidified air enters the dryer where water removed from the wet product. Meanwhile, in the regenerator zone of the rotating wheel the saturated adsorbent is dried by using hot air from a heater. In the regenerator the temperature of air decreases while the vapor content increases.

3. Heat recovery and multistage drying

The main reason for the low energy efficiency in drying is the heat loss in the off-gas from the dryer. The off-gas flow has a significant energy content since the air contains a high amount of vapor from which the latent heat can be recovered by condensation (see Figure 1.4). Kemp[22] applied pinch analysis formulated by Linnhoff[23] to recover energy in conventional drying systems in order to minimize energy usage, but concluded that for straightforward conventional dryers the options to reduce energy are limited. Krokida and Bisharat[24] investigated the potential of heat exchangers, heat pumps, and combinations of heat exchangers and heat pumps for recovery of sensible and latent heat. The result indicated that 40% of heat loss in the off-gas can be recovered. However, after taking the amount of energy to realize this into account the improvement of energy efficiency is marginal and ends at 60%. Iguaz et al[25] proposed the enhancement of thermal efficiency by recycling exhaust gas from dyers operated above 200°C, but the energy efficiency comes not further than 65%. Moreover, the system is only suitable for high temperature drying with superheated vapor.

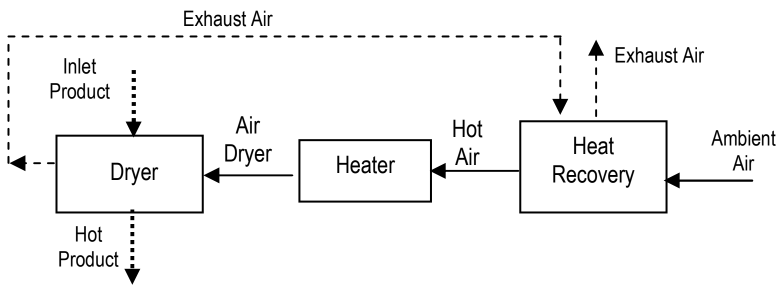

Figure 1.4: A schematic diagram of a dryer combined with heat recovery to reuse heat of exhaust air and hot product from dryer. Ambient air is heated in the heat recovery unit using exhaust air from the dryer and hot product leaving dryer. Subsequently, hot air is heated-up to dryer temperature, and then it passes the dryer to remove water from the product. Latent and sensible heat in the exhaust air are recovered in the heat recovery unit.

Multistage drying can also be an option to improve efficiency.[26,27] In this system, the exhaust air of a dryer is heated again and re-used for a next drying stage. Figure 1.5 gives in a psychometric chart a comparison of a single-stage and a multistage dryer.[26,27] Important advantages of this multistage system is that high air temperatures in inlet air are avoided and the required air flow is below that for a standard dryer. However, the temperatures in the second, third and next stages increase gradually due to higher moisture content in air after contacting wet product.

The multistage dryer system provides important benefits compared to conventional single-stage dryer systems. The evaluation of Holmberg and Ahtila[27] showed that the investment and operational cost of the multistage dryer competes with a single-stage dryer over a longer amortization time. The best improvement of energy efficiency was achieved for operational temperatures below 100°C with 2-4 drying stages where energy savings around 10% can be achieved. However, for operational temperatures above 100°C the improvement is not significant.[28]

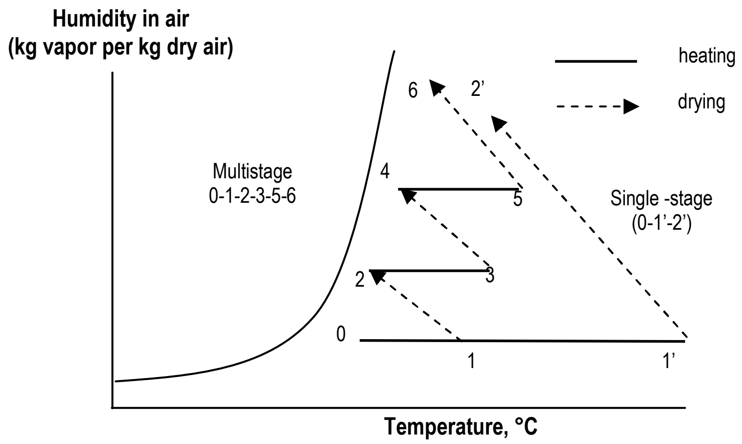

Figure 1.5: Comparison of a single-stage and a multistage conventional dryer.[26,27] The single stage dryer requires a high temperature and purges exhaust air at a higher temperature which implies more heat loss. In the multistage dryer, the drying can be carried out gradually, which requires lower dryer temperatures and results in a lower exhaust air temperature.

4. Research challenges

This research focuses on multistage adsorption dryers using zeolite as vapor adsorbent. zeolite is selected as adsorbent since it can remove nearly all vapor from air. Hence, the driving force for drying at low and medium temperature drying is increased which yields a high drying rate while retaining quality of heat sensitive products. Other experimental work also showed the suitability of zeolite for adsorption drying.[14-17,29] A heat recovery unit based on a heat exchanger network and air compressor is used in this research to recover sensible and latent heat from the off-gas. The challenges for research on drying at low and medium operational temperatures are:

1. How to use the zeolite to enhance the energy efficiency of drying systems
2. How to recover heat flows in dryer-adsorption-regeneration system
3. What is the potential for a multistage zeolite drying system?
4. How to design the zeolite drying process operation with proper dimension equipment?
5. Can the zeolite drying system be validated
6. How to use the obtained knowledge to design an energy effective dryer?

Figure 1.6 presents a possible construction of a multistage zeolite dryer. The main benefit is that the energy content of the exhaust air is reused several times. Moreover, the released adsorption heat is utilized to heat the air for drying in the succeeding stages. As a consequence, product drying hardly requires heat supply. The regeneration of spent zeolite from the adsorbers requires heat supply, but with pinch based heat recovery the net energy input can be kept low.

Compared to conventional multistage dryers the concept has more benefits since the vapor content of the air for the succeeding stages is lower (see Figure 1.7). Hence, the operational temperature for drying can be also kept low in order to retain product quality and improve driving force for drying.

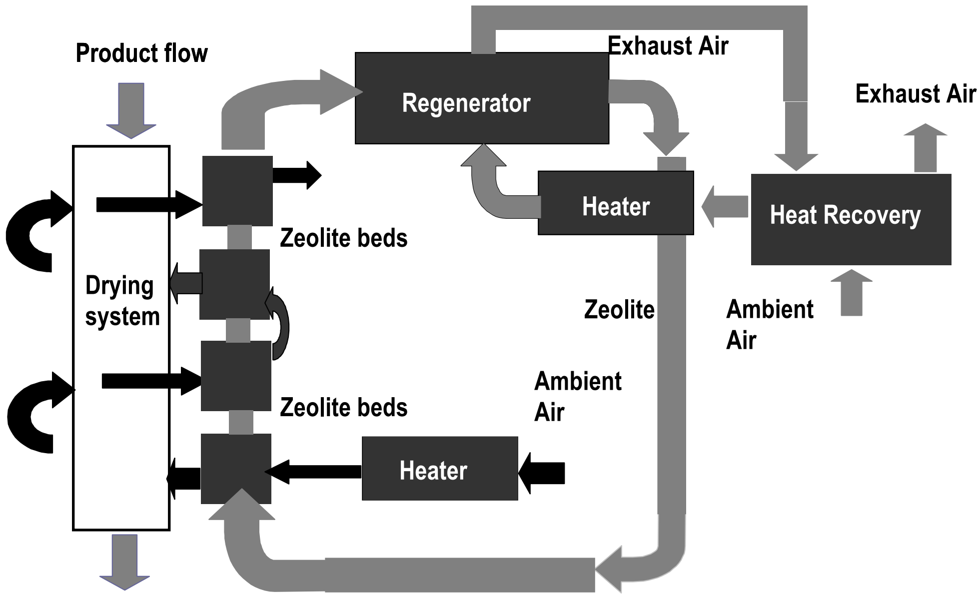

Figure 1.6: A suggested lay-out for counter-current multistage zeolite dryer. Ambient air is heated up in a heater and after dehumidification the air is used for product drying. Exiting the dryer, the vapor in air is removed in a second adsorber and used for drying again. This process is repeated several times depending on the number of stages. The spent zeolite from the last adsorber stage is re-activated in the regenerator using hot air obtained by heating-up ambient air in a heat recovery unit and a heater.

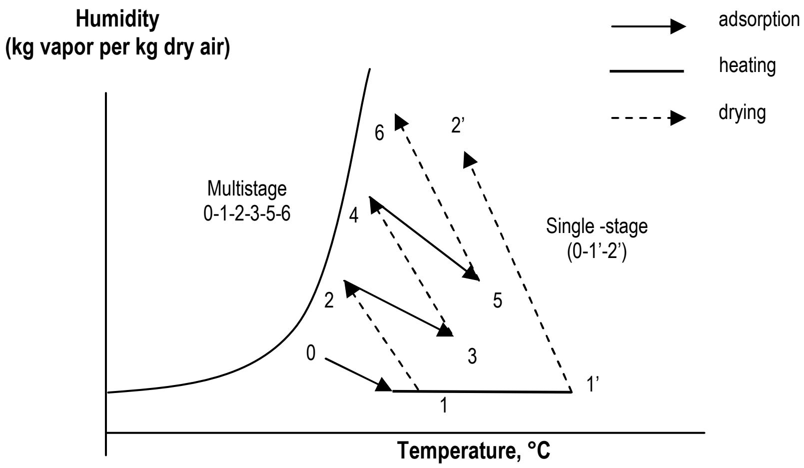

Figure 1.7: Psychometric chart of air. A. Comparison of a single-stage and a multistage zeolite dryer. Fresh air is fed to the system at position 0. After adsorption and/or heating position 1 is reached for the multistage systems and 1' for the single-stage systems. From this point the multistage systems continue with drying, adsorption or heating along the path 1-2-3 etc until 6. The single-stage system continues to 2'.

5. Research activities

The research aims the development of a multistage drying system using zeolite as adsorbent. The work will is based on five main steps:

1. Evaluation of energy efficiency in a conventional drying system and process integration for an adsorption drying system using zeolite,
2. Development of multistage drying system to improve drying efficiency,
3. Evaluation of energy efficiency multistage zeolite drying system for low dryer temperature,
4. Characterization of spatial distribution of temperature and moisture in a multistage zeolite drying by computational fluid dynamics for designing dryer equipment,
5. Experimental validation to prove parts of the concept.

6. Thesis Outline

Chapter 2 concerns the comparison between conventional dryers and a single-stage dryer using air dehumidified by zeolite. Steady-state mass and energy balances have been used and the work concerns drying temperatures ranging from 50-70 °C. Process integration based on pinch analysis has been applied and nine different heat exchanger networks for energy recovery are compared.

Chapter 3 studies the potential of three multistage zeolite drying systems (counter, co, and cross-current) with a varying number of stages. The study was done to evaluate energy efficiency for the multistage system and the effect of the stage number for the energy efficiency. In doing so, a compressor has been applied to recover latent heat from exhaust air for heating up air as drying medium in additional convective dryer.

Chapter 4 is a continuation of chapter 3 where counter current multistage adsorption dryer using zeolite and alumina pillared clay are evaluated and compared with conventional condensation dryers at various ambient air conditions and operational drying temperatures.

Chapter 5 discusses computational fluid dynamics (CFD) modeling for a multistage adsorption dryer. The aims of this chapter are to identify the profiles for moisture and temperature distribution in the adsorber, dryer and regenerator, and to draw conclusions on proper dimensions of a multistage zeolite dryer, residence time of air, product and zeolite. Using this information the dimensions of multistage adsorption dryers can be determined. Evaluation showed that energy efficiency of a multistage zeolite dryer designed by using CFD is close to previous model calculations performed with a steady-state lumped model.

Chapter 6 is experimental work to validate the drying concept using adsorbents. The experimental equipment uses a shift adsorber-regenerator system. The energy efficiency is derived from the experimental results, the heat recovery potential, the required heat for regeneration, the released adsorption heat, and the heat for drying. The results show that the energy efficiency is close to the model calculations done in previous chapters.

Chapter 7 presents a general discussion to evaluate the multistage zeolite dryer concept and to formulate further development to bring the system towards the users. Several options have been formulated to construct the zeolite dryer in continuous operating systems using belt moving bed and rotating wheel of zeolite. This retrospect shows that there are a number of potential solutions to bring the concept of multistage zeolite drying to industrial application.

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Chapter 2

Process Integration for Food Drying with Air Dehumidified by Zeolites

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Abstract

Zeolites have potential to increase efficiency of medium temperature drying in the food industry. This work concerns the comparison between conventional dryers and dryers using air dehumidified by zeolite. Steady-state mass and energy balances have been used and the work concerns drying temperatures ranging from 52-70 °C. Process integration based on pinch analysis has been applied and nine different heat exchanger networks for energy recovery are compared. Results indicated that dryers using air dehumidifier by zeolites are 10-18% more efficient than conventional dryers.

Keywords: adsorption; energy efficiency; process integration; zeolite drying

Nomenclature

A_{exc}	heat exchanger area	(m^2)
c_p	specific heat	(kJ/kg°C)
F	mass flow of dry medium	(kg/hr)
H	flow of enthalpy	(kJ/hr)
ΔH_v	latent heat of water evaporation	(kJ/kg)
ΔH_{ads}	latent heat of water adsorption	(kJ/kg)
Q	energy exchange with external utility	(kJ/hr)
RH	relative humidity	(%)
T	temperature	(°C)
U	overall heat transfer coefficient	($kJ/m^2hr°C$)
X	water content in solid material	(kg water/kg dry material)
Y	moisture content in air	(kg water/kg dry air)
$LMTD$	logarithmic mean temperature difference	
A	air stream	
P	product stream	

Subscripts

a	dry air	*ad*	adsorber	*ads*	adsorption
c	cold stream	*co*	cooler	*d*	dryer
des	desorption	*ex*	exhaust	*evap*	evaporation
h	hot stream	*he*	heater	*in*	inlet
out	outlet	*p*	product	*r*	regenerator
sat	saturated	*v*	vapor	*w*	water
z	zeolite	1,2..	stream number		

1. Introduction

Convective drying is a major operation in the food industry. Liquid products as milk are dried with air temperatures up to 200°C. Products, in which water is captured in a solid matrix (vegetables, herbs, starch products) are dried at low (10°C) to moderate temperatures (50-90°C) to conserve the quality of the essential components (protein, vitamins, enzymes, oil) and to retain the appearance (color, shape and texture). Drying at low to moderate temperatures has a low energy efficiency as main drawback. For example, with an inlet temperature of 90°C, the mean value for the exhaust temperature for tea drying is around 60°C.[1] For an ambient temperature of 30°C, the efficiency is 50%. Energy efficiency of drying, which depends on factors as temperatures, flow rates, initial moisture content, and also dryer design,[2] is therefore an important issue for the food industry.

The drying capacity of the air in convective dryers depends on the temperature and the moisture content of the air. Options to increase the drying capacity are:

- increasing temperature at constant absolute moisture content
- lowering the absolute moisture content at a given temperature, or
- a combination of both

Because of the heat sensitivity of many food products increasing the temperature is not a good solution to improve efficiency. Changing the water content of the air is an attractive option.

Zeolites have a high potential for water adsorption and can be applied in dryers to improve the water uptake capacity of the air at low temperatures.[3] The application of zeolite for water adsorption is widely investigated for many purposes.[4-8] Research in immersion drying of wheat with a range of adsorbing materials (synthetic zeolite, natural clay, pillared aluminum clay, and sand) showed that the zeolite has the highest moisture uptake capacity from the product. [9]

When water is adsorbed by a zeolite the adsorption heat will increase the air temperature. As a result the energy needed for drying reduces significantly. However, the major drawback that hampers in the use of zeolite as a water adsorbent in drying is the energy needed for regeneration of the saturated zeolite (temperatures in the range 90-300°C are needed[7,10]) and which decreases the saved energy for drying. Zeolite regeneration yields off-gasses at rather high temperatures and increased moisture content. One option is to use the off-gasses for other processes, e.g. the steam generator of the plant. Another option is to apply process integration principles in order to obtain a good concept for recovering the heat released from the regeneration process.

Process integration is a systematic and generic method for designing integrated production systems, with special emphasis on the efficient use of energy and reducing the environmental effects.[11] In practice, process integration is based on applying pinch technology and on generating an optimal process configuration. Pinch technology is based on the first and second laws of thermodynamics, which uses a minimum driving force for energy transfer called pinch temperature.[12] The method has been widely used in various sectors and resulted in significant energy reductions and lower environmental effects.[13-22] Based on the track record, process integration offers potential for the development of efficient zeolite based drying systems.

This work concerns the use of zeolites in moderate temperature drying for food applications. First, a zeolite drying system is compared with a conventional drying system by using steady state mass and energy balances. Secondly, it is shown that compared to a conventional dryer the energy efficiency of a zeolite dryer with process integration is higher. The calculations are based on a dryer with an air flow of 1000 kg/hr. Although its concerns a small dryer, the results on energy efficiency do not change for other scales; the heat exchanging area follows from a linear scale-up.

2. Zeolite dryer versus conventional dryer

2.1 Zeolite drying system

Figure 2.1 presents the zeolite dryer system, which consists of an adsorber, heater, dryer, and regeneration unit. The adsorber uses zeolite to reduce the humidity of the air to 10% of its initial humidity. The air enters the adsorber at ambient temperature and due to the release of the adsorption heat the air leaves the adsorber at a higher temperature. Before charging to the dryer, air can be heated additionally to the required drying temperature using saturated steam and returning the condensate to the steam supplying utility. The air is fed into the dryer where it contacts the wet product and the sensible heat of the air is used to evaporate water. Because of the low water content of the air, the water uptake capacity is higher and thus a lower air flow is needed. Meanwhile, the saturated zeolite from the adsorber is dried in the regeneration unit to obtain dry zeolite for reuse in the adsorption unit. The regeneration system uses hot air, heated with steam, with a temperature in the range of 90-300^{o}C. A higher temperature gives a better regeneration. Dry zeolite is cooled down before feeding to adsorber by indirect cooling with cold air. In this case a first step for energy recovery is already applied by using the exhaust air of the dryer for regeneration. Even nearly saturated air from the dryer is after heating to 200-300°C suitable for regeneration (RH<1%). The stream conditions used for the calculation are given in Appendix 2.1. The calculations results (given in Table 2.1a) concern a small dryer with only 1000 kg air/hr, but results can be extrapolated linearly to larger systems. Note: in the picture a symbol for a spray dryer unit is used, but any convective dryer can replace it.

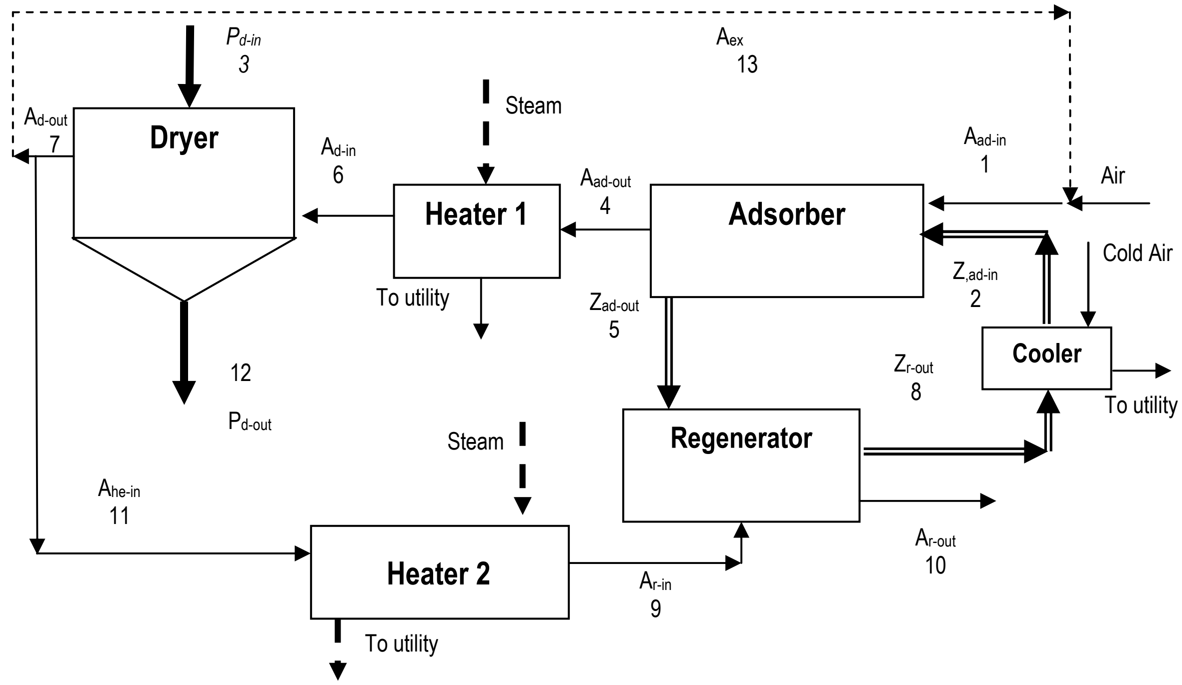

Figure 2.1: Dryer with zeolite dehumidified air; the numbers give the tags for the streams

Stream 13 also can be directly recycled by mixing with fresh air in order to minimize the use of ambient air and to retain the energy in the dryer exhaust air. As a result the required heat in heater 1 is reduced because the recycle temperature is higher than the ambient temperature. In this way, the total energy consumption can be reduced. However, the heat required in Heater 2 increases due to higher water content that has to be released. The result of estimation can be seen in Table 2.1b.

2.2 Conventional drying system

Figure 2.2 presents a conventional drying system in which the same wet material is dried. The system consists of a heater to increase air from ambient temperature to the required drying temperature, and a dryer to dry the product. The conditions for drying are given in Appendix 2.1.

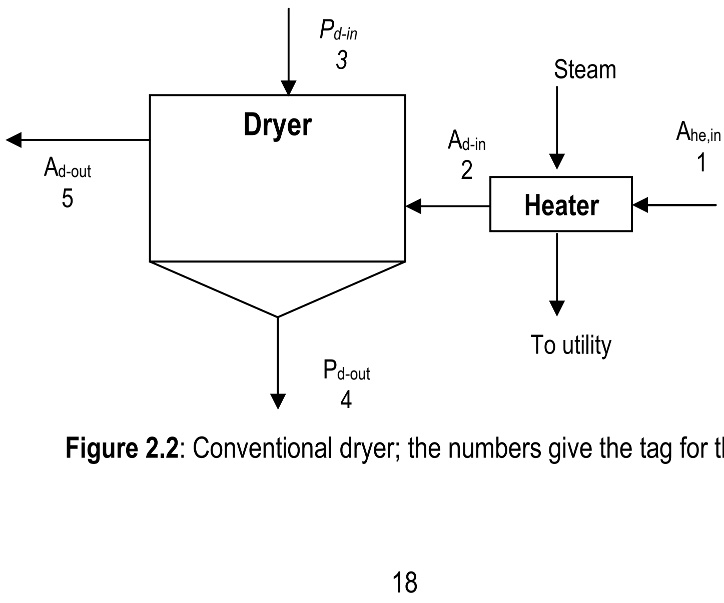

Figure 2.2: Conventional dryer; the numbers give the tag for the streams

2.3. Mass and energy balances

For the calculations both drying systems are split into sub systems. Steady-state models for the subsystems, based on the conservation of mass and enthalpy are used. Assumptions for the calculations are:

- adiabatic processes for the subunits,
- constant physical properties (density, specific heat),
- pressure drop is excluded from the calculations,
- operational pressure 1 bar,
- well mixed subsystems,
- in all cases the exhaust air of the dryer has a relative humidity of 40%,
- in the adsorption unit 90% of moisture content in the air is removed,
- at the exit of each unit air and solid material have the same temperature
- the enthalpy reference is 0°C

Values used for calculations are given in Table A1-1, Appendix 2.1.

a. Adsorber (see Figure 2.3**)**

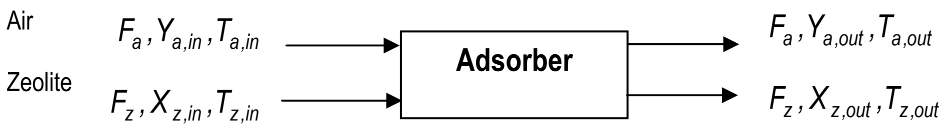

Figure 2.3: Adsorber input-output streams

Assumptions

- Calculations are based on dry air and dry zeolite flows
- Dry air flow in equals dry air flow out: $F_{a,in} = F_{a,out} = F_a$
- Dry zeolite flow in equals dry zeolite flow out : $F_{z,in} = F_{z,out} = F_z$

The water mass balance is:

$$F_a Y_{a,in} + F_z X_{z,in} = F_a Y_{a,out} + F_z X_{z,out} \qquad (1)$$

The enthalpy balance for the adsorber is:

$$H_{a,in} + H_{z,in} = H_{a,out} + H_{z,out} + H_{ads} \tag{2}$$

$$H_{a,in} = F_a((c_{p,a} + Y_{a,in}c_{p,v})T_{a,in} + \Delta H_v Y_{a,in}) \tag{3}$$

$$H_{z,in} = F_z(c_{p,z} + X_{z,in}c_{p,w})T_{z,in} \tag{4}$$

$$H_{a,out} = F_a((c_{p,a} + Y_{a,out}c_{p,v})T_{a,out} + \Delta H_v Y_{a,out}) \tag{5}$$

$$H_{z,out} = F_z(c_{p,z} + X_{z,out}c_{p,w})T_{z,out} \tag{6}$$

$$H_{ads} = \Delta H_{ads}(X_{z,out} - X_{z,in})F_z \tag{7}$$

Physical constants and operational conditions are given Table A1-1, Appendix 2.1. The required zeolite flow and outlet temperature of the adsorber are results of the calculations. *Note*: In the calculation results not the dry air and zeolite flows are represented, but the wet air and zeolite flows. Note: in the calculation results not the dry air and zeolite flows are represented, but the wet air and zeolite flows. Mass flow of each stream contain dry material or air and moisture; see note (*) in Tables 1a and 1b.

b. Regenerator

The mass and enthalpy balances for regenerator are almost equal to that of the adsorber. However, here energy is required to release water from the zeolite.

$$H_{a,in} + H_{z,in} - H_{des} = H_{a,out} + H_{z,out} \tag{8}$$

$$H_{des} = -H_{ads} \tag{9}$$

Those balances are used to calculate the temperature and air humidity of the outlet streams. Analog equations as given for the adsorber are used.

c. **Heater** (see Figure 2.4)

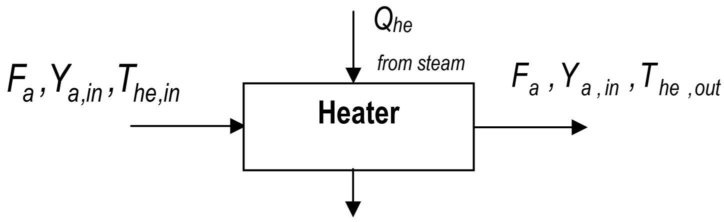

Figure 2.4: Heater input-output streams

The aim of this calculation is to estimate required amount of external heat. The steam flow is not considered since after transferring heat, it changes to condensate which is sent to steam boiler. In the heater no mass exchange takes place; so only the enthalpy balance has to be considered. The enthalpy balance for the heater is given as balance form:

$$H_{a,in} + Q_{he} = H_{a,out} \tag{10}$$

The inlet and outlet air enthalpy follow from the stream conditions. The required heat for the heater is calculated.

d. Dryer (see Figure 2.5)

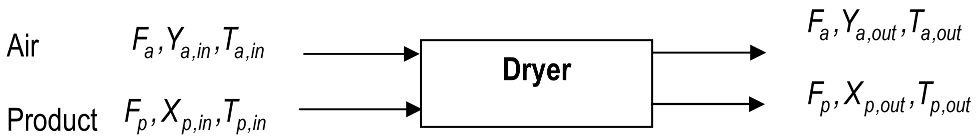

Figure 2.5: Dryer input-output streams

Assumptions

- Calculations based on dry air and product flows
- Dry air flow in equals dry air flow out: $F_{a,in} = F_{a,out} = F_a$
- Dry product flow in equals dry product flow out : $F_{p,in} = F_{p,out} = F_p$

In the dryer mass and energy exchange take place. The water balance using dry basis air and product flow are as follows:

$$F_a Y_{a,in} + F_p X_{p,in} = F_a Y_{a,out} + F_{p,out} X_{p,out} \tag{11}$$

$$Y_{a,out} = RH.Y_{sat} \tag{12}$$

where Y_{sat} represents the water vapor saturation line in the psychometric chart and depends on outlet dryer temperature ($T_{d,out}$), which follows from the enthalpy balance of dryer. The balances are:

$$H_{a,in} + H_{p,in} = H_{a,out} + H_{p,out} + H_{evap} \tag{13}$$

$$H_{p,out} = F_p (c_{p,p} + X_{p,out} c_{p,w}) T_{p,out} \tag{14}$$

$$H_{evap} = \Delta H_v (X_{p,in} - X_{p,out}) F_p \tag{15}$$

$$H_{p,in} = F_p (c_{p,p} + X_{p,in} c_{p,w}) T_{p,in} \tag{16}$$

Physical constants and operational conditions are given Table A1-1, Appendix 2.1. The product moisture content leaving the dryer ($X_{p,out}$) is set to 0.111 kg water/kg dry product, and outlet temperature of product and air equals ($T_{p,out} = T_{a,out} = T_{d,out}$). The flow of dry product and outlet dryer temperature are result of the calculations. The effect of product/air temperature on product moisture at given relative humidity proved to be minimal and is neglected. Note: in the calculation results not the dry air and zeolite flows are represented, but the wet air and zeolite flows. Mass flow of each stream contain dry material or air and moisture; see note (*) in Tables 2.1a and 1b.

e. Cooler (see Figure 2.6)

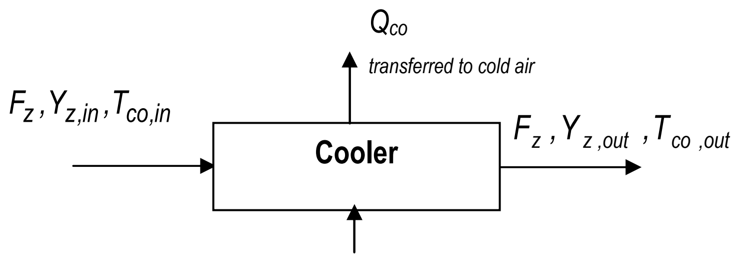

Figure 2.6: Cooler input-output streams

The aim of this calculation is to estimate amount of heat to be removed in cooler. Here, cold air is used to cool hot zeolite exiting regenerator. In this unit no mass exchange takes place; so only the enthalpy balance has to be considered. The enthalpy balance for the cooler is as follows:

$$H_{z,in} = Q_{co} + H_{z,out} \quad (17)$$

The inlet and outlet air enthalpy follow from the stream conditions. The required cooling capacity is calculated.

2.4 Comparing zeolite and conventional drying system

The results for the zeolite and conventional drying systems are summarized in Table 2.1a and Table 2.1b. The tables present the mass and energy flows at different points in the system and temperature and moisture content of each flow.

Table 2.1a: Results of drying with dehumidified air without recycle

Stream Number	Temperature °C	Moisture kg/kg	Wet Mass Flow kg/hr*	Enthalpy Flow (*H*) kJ/hr
1, $A_{ad\text{-}in}$	25.00	0.0100	1000	49983
2, $Z_{ad\text{-}in}$	35.00	0.0000	45	1304
3, $P_{d\text{-}in}$	25.00	2.3333	21	1864
4, $A_{ad\text{-}out}$	51.62	0.0010	991	53679
5, $Z_{ad\text{-}out}$	51.62	0.2000	54	3845
6, $A_{d\text{-}in}$	70.00	0.0010	991	71916
7, $A_{d\text{-}out}$	35.40	0.0150	1005	73192
8, $Z_{r\text{-}out}$	141.19	0.0000	45	5259
9, $A_{r\text{-}in}$	300.00	0.0150	201	68551
10, $A_{r\text{-}out}$	141.19	0.0600	210	60900
11, $A_{he\text{-}in}$	35.40	0.0150	201	14638
12, $P_{d\text{-}out}$	35.40	0.1111	7	588
13, A_{ex}	35.40	0.0150	804	58553
	$Q_{he,1} = H_6 - H_4$			**18237**
	$Q_{he,2} = H_9 - H_{11}$			**53913**
	Total Heat required = $Q_{he,1} + Q_{he,2}$			**72150**
	$Q_{co} = H_8 - H_2$			**3955**
	Total heat removed= $-Q_{co}$			**-3955**

*Based on wet flow e.g: $A_{ad\text{-}in} = F_a\,(1+Y_{a,in})$

Table 2.1b: Results of the conventional dryer

Stream Number	Temperature °C	Moisture kg/kg	Wet Mass Flow kg/hr*	Enthalpy Flow (*H*) kJ/hr
1, $A_{he\text{-}in}$	25.00	0.0100	1212	60588
2, $A_{d\text{-}in}$	70.00	0.0100	1212	115638
3, $P_{d\text{-}in}$	25.00	2.3333	21	1864
4, $P_{d\text{-}out}$	41.72	0.1111	7	693
5, $A_{d\text{-}out}$	41.72	0.0216	1226	116809
	$Q_{he} = H_2 - H_1$			**55050**
	Total heat required			**55050**

*based on wet flow

As the zeolite system uses nearly dry air the wet bulb temperature of the air is about 6°C below the wet bulb temperature for the conventional dryer. It gives some benefit for the energy efficiency, but more important, the mean product temperature in the dryer will be lower and thus degradation of product quality due to heat load is lower.

The drying capacity is related to the difference between the moisture content in inlet air and for air with 40% relative humidity. The difference for the dehumidified air is larger than for the fresh air and therefore the zeolite dryer needs about 20% less air than the conventional dryer.

Due to the released heat of adsorption, the energy for heating the air is only 25% of the energy needed for the conventional dryer. However, the overall zeolite drying system needs about 30% more energy than the conventional dryer (72150 kJ/hr ($Z_{ad\text{-}out}$ to $A_{d\text{-}in}$ in Table 2.1a) versus 55050 kJ/hr ($A_{he\text{-}in}$ to $A_{d\text{-}in}$ in Table 2.1b)). This result is due to the high amount of energy for regeneration and the high energy content of the off-gas streams.

The temperature of the regenerator exhaust (130-140°C) and the energy content of the exhaust are favourable for recovery. The first option is to bring the flow directly to the steam generation unit of the plant. For example, in a direct contact water preheating unit at least 50% of the energy is recovered (33000 kJ/hr). This form of reuse yields in combination with the dryer a minimal energy reduction of 25-30% compared to the conventional dryer. Another option is to apply process integration where energy recovery is realised within the drying system (see next section).

2.5. Varying drying temperatures and recycle

The effectiveness is also calculated for varying drying temperatures. For lower inlet air temperatures the heat to preheat the air, entering the dryer, reduces as well as the total of heat consumption. The results in Table 2.2 indicate that for the zeolite drying system the required heat is still higher than for the conventional dryer. Main reason is that the heat for regeneration is higher than that of drying. As can be seen in Table 2.2, when the dryer temperature is reduced up to 51.6°C, the air does not need heat before entering the dryer.

Another alternative is the complete recycling of the exhaust air from the dryer (stream 13). The use of exhausted heat from the dryer exit reduces the need of fresh air feed and because more water is removed in the adsorber the outlet temperature of the adsorber increases up to 71.2°C (see Table 2.3). As a consequence no additional heating is necessary. In this case, the total required heat is 64064 kJ/hr and is 12% below the energy needed for the zeolite dryer without recycle. However, the energy consumption is still higher than that for the conventional dryer at the same conditions. By implementing heat recovery, it is expected, the total of heat required can be significantly reduced.

Table 2.2: Effect of inlet air dryer temperature on total heat required

Inlet Air	Drying with dehumidified air						Conventional Dryer		
	Temp. stream 7 °C	Temp. stream 10 °C	Q* Dryer kJ/hr	Q** Reg kJ/hr	Total energy kJ/hr	Air flow kg/hr	Temp. stream 5 °C	Q* Dryer kJ/hr	Air flow kg/hr
70.00	35.40	141.19	18237	53913	72150	1000	70.00	55050	1212
60.00	32.08	140.57	8317	54318	62635	1000	60.00	46746	1323
51.62	28.96	140.07	0	54732	54732	1000	51.62	40389	1503
Air recycling									
71.22	36.00	132.69	0	64064	64064	1005	71.12	56300	1207

* heat required to increase air temperature for drying ** heat required to increase air temperature for regeneration

Table 2.3: Result of drying with dehumidified air and recycling stream 13

Stream Number	Temperature °C	Moisture kg/kg	Mass Flow kg/hr	Enthalpy Flow kJ/hr
1*, $A_{ad\text{-}in}$	34.39	0.0146	1005	71064
2, $Z_{ad\text{-}in}$	35.00	0.0000	65	1899
3, $P_{d\text{-}in}$	25.00	2.3333	21	1898
4, $A_{ad\text{-}out}$	71.22	0.0015	992	74321
5, $Z_{ad\text{-}out}$	71.22	0.2000	78	7729
6, $A_{d\text{-}in}$	71.22	0.0015	992	74321
7, $A_{d\text{-}out}$	36.00	0.0157	1006	75609
8, $Z_{r\text{-}out}$	132.69	0.0000	65	7200
9, $A_{r\text{-}in}$	350.00	0.0157	201	79186
10, $A_{r\text{-}out}$	132.69	0.0813	214	70628
11, $A_{he\text{-}in}$	36.00	0.0157	201	15122
12, $P_{d\text{-}out}$	36.00	0.1111	7	609
13,A_{ex}	36.00	0.0157	805	60488
$Q_{he,1} = H_6 - H_4$				**0**
$Q_{he,2} = H_9 - H_{11}$				**64064**
Total Heat required = $Q_{he,1} + Q_{h,2}$				**64064**
$Q_{co} = H_8 - H_2$				**5301**
Total heat removed= $-Q_{co}$				**-5301**

* combining fresh air with stream 13

3. Process Integration

Kemp[23] gives a clear explanation on pinch analysis and the application to conventional drying systems. For straightforward conventional dryers the options to reduce energy are limited.[23] The zeolite drying system is more complex and there is a higher potential for heat recovery.

The energy levels of stream 8 and stream 10 (Figure 2.1, Table 2.1) is significant and their temperatures are satisfying for heat recovery. Stream 10 concerns the exhaust air from the regenerator and is released to the environment and stream 8 is dry zeolite that must be cooled before re-entering the adsorber. In contrast, streams 4 and 11 need energy in order to reach the required conditions for drying and regeneration.

3.1 Applying process integration to the zeolite drying system

The aim is to recover the sensible heat of the hot streams and to use it for heating cold streams. The objective is achieved by following the next steps for pinch analysis:

- identify hot and cold streams conditions in the system and targeted temperatures that have to be achieved

- configure temperature intervals and composite curves to determine the maximum energy can be transferred, minimum hot and cold utility required and pinch point temperature
- match the possible hot and cold streams of the process to reduce external energy use
- estimate energy recovery by introducing a number of heat exchangers

Table 2.4: Hot and cold stream conditions for dehumidified air drying (Figure 2.1)

Stream	Source		Target		Heat capacity kJ/ °C hr	Q kJ/hr
	Stream	Temperature °C	Stream	Temperature °C		
Cold 1	11, $A_{he\text{-}in}$	51.62	9	300	203.75	53913
Cold 2	4, $A_{ad\text{-}out}$	35.40	6	70	992.01	18237
	Total external heat required					**72150**
Hot 1	8, $Z_{r\text{-}out}$	141.19	2	35	37.25	3955
Hot 2	10, $A_{r\text{-}out}$	141.19	exhaust	45	220.95	21254
	Total heat released					**25209**

Table 2.4 shows that systems needs 72150 kJ/hr, while 25209 kJ/hr is released. With full energy recovery minimally 46941 kJ/hr is needed, which is around 15% below the energy needed for the conventional dryer. Streams 11 and 4, can be heated by using stream 8 and/or 10. By matching these streams, it is expected that the main part of all potential energy can be recovered.

3.2. Identifying energy recovery from pinch analysis

First a scheme with the cold and hot streams and their temperature intervals is made (see Douglas[24]). Using a minimal required driving force (ΔT =10°C) yields the results in Figure 2.7, the temperatures for hot and cold stream are presented (see Figure 2.7). In each the interval, heat transfer is given by the following equation:

$$Q_{interval,i} = \left[\sum (F_h c_p)_{h,i} - (F_c c_p)_{c,i}\right]\Delta T_{interval,i} \tag{18}$$

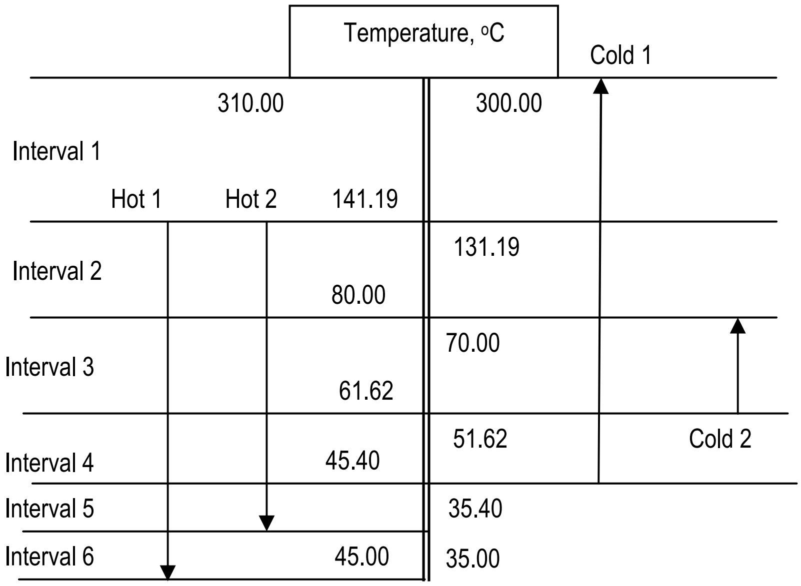

Figure 2.7: Temperature interval for hot and cold stream

Table 2.5: Heat transfer in each interval

Interval	$\Delta T_{interval}$ °C	Heat capacity $F_h c_{p,h}$ (kJ/hr°C)			Heat capacity $F_c c_{p,c}$ (kJ/hr°C)			$Q_{interval}$ (kJ/hr)
		1	2	total	1	2	total	
1	168.81				203.75		203.75	-34395
2	61.19	37.25	220.95	258.2	203.75		203.75	3331
3	18.38	37.25	220.95	258.2	203.75	992.01	1195.76	-17232
4	16.22	37.25	220.95	258.2	203.75		203.75	883
5	0.4	37.25	220.95	258.2			0	103
6	10	37.25		37.25			0	373

Table 2.5, represents the heat transfer between hot and cold streams and shows that heat is required for intervals 1 and 3. The surplus heat available from interval 2 can be used in interval 3, but not in interval 1. The surplus heat from interval 4-6 cannot be used because of the low temperatures. As a result, the system needs minimally 34395-3331+17232≈48300kJ/hr external heat. This value is below that for the system without recovery (72150 kJ/hr see Table 2.1a). Thus, the total heat that can be recovered is 23850kJ/hr. In addition, the system needs minimally 883+103+373≈1360 kJ/hr for cooling the hot streams the intervals 4-6 to the target temperature.

Figure 2.8 gives the composite curves where the enthalpy of coldest hot stream temperature is defined as a reference point (*H*=0).[24] The temperatures of hot and cold streams are plotted against the cumulative heat of cold and hot stream. The curves are not crossing and the pinch-point with a temperature difference of 10°C is located at 45.4°C for the hot stream and 35.4°C for the cold stream. Hence, this system is suitable for direct heat recovery.

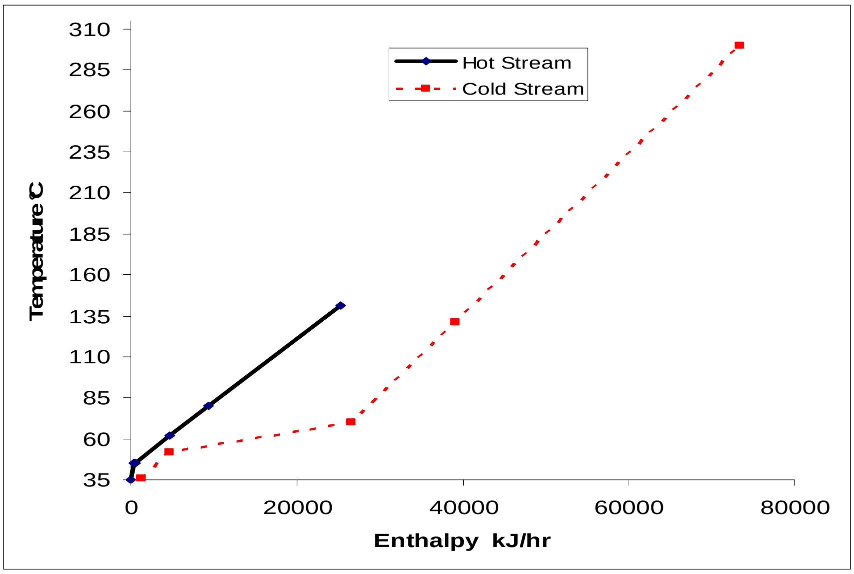

Figure 2.8: Composite curve of hot and cold stream

3.3. Heat exchanger network configuration

The hot and cold composite curves show that the possible matches are located above the pinch point. Hot streams can be matched with cold stream when it has lower heat capacity ($Fc_{p,c} \geq Fc_{p,h}$).[24]

Hot 2 cannot be optimally used to heat cold 1, while hot 1, with lowest heat capacity can directly be used to heat either cold 1 or cold 2. In addition, cold 2 with highest heat capacity can be matched to both hot 1 and 2. So, the heat exchanger network for heat recovery can be generated in two ways. The first is a direct matching of cold 2 with hot 2, and cold 1 with hot 1 (see Figure 2.9). The second is splitting hot 2 in order to bring the heat capacity of the separate streams below that of both cold streams. Now, the divided hot stream is matched with both cold streams. The best solution can be found by evaluating the total quantity of energy that is transferred, the required heat exchanger area, the amount of energy transferred per unit of area, and the total of energy needed after integration.

3.3.1. Direct matching

The direct match is made of combining hot 2 with cold 2 and hot 1 with cold 1, as presented in Figure 2.9 called as network 1.

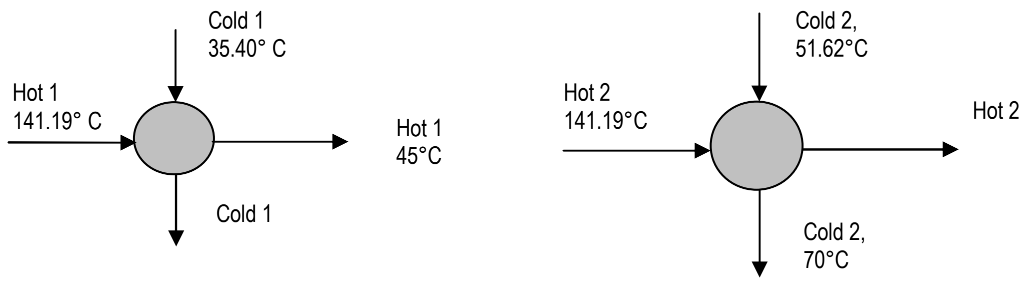

Figure 2.9: Heat exchanger configuration for a direct match (network 1)

Heat exchanger calculations based on the following assumptions were performed:

- a minimum temperature difference of 10°C,
- an overall gas-to gas heat transfer coefficient of 50 kJ/m²hr°C(=13.89 W/m².°C) [25]
- an adiabatic process,
- constant physical properties (density, specific heat),
- counter current heat exchanger.

The used expressions are:

$$T_{h,out} = T_{c,in} + 10 \quad (19)$$

$$Q_h = F_h c_{p,h} (T_{h,out} - T_{h,in}) \quad (20)$$

$$\sum Q_{h,i} + \sum Q_{c,i} = 0 \quad (21)$$

$$Q_{c,i} = F_c c_{p,c} (T_{c,out} - T_{c,in}) \quad (22)$$

$$Q_{h,i} = UA_{exc} \Delta T_{LMTD} \quad (23)$$

$$\Delta T_{LMTD} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{ln \frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}} \quad (24)$$

The results presented in Table 2.6 show the potential energy recovery. The total heat transferred from hot streams to cold streams is 21149 kJ/hr, i.e. 89% of the available energy identified from the pinch analysis (23850 kJ/hr). For the heat exchanger a total area of 13.20 m² is required, and the total heat transferred per unit of area is 1602.61 kJ/m²hr. Around 11% of the available heat in hot 1 and 2 is not recovered. Hot 2 has still potential for a higher degree of reuse due to the high energy content and temperature.

Table 2.6: Results for direct match

Stream	Temperature In °C	Heat capacity flow kJ/hr°C	Temperature Out °C	*Q*-recovery kJ/hr	A_{exc} m²	*Q*-rec./A_{exc} kJ/m².hr
Cold 1	35.40	203.75	52.91	3568	1.99	1602.61
cold 2	51.62	992.01	69.34	17581	11.21	
Total				**21149**	**13.20**	
hot 1	141.19	37.25	45.40	-3568		
hot 2	141.19	220.95	61.62	-17581		

3.3.2. Splitting streams

Hot 2 (stream 10) cannot be optimally used by matching with cold 1, but dividing the stream in two streams and adjusting their flows in such a way that the heat capacity of each flow becomes below that of cold 1 will give an optional match to the cold streams. Several heat exchanger networks are generated, as illustrated in Appendix 2.2.

The direct match method from section 3.3.1 can be used as reference to find the network with the best performance. For each network the optimal ratio of the split flows is determined. The optimisation is constrained by the need that heat capacity in each stream has to be lower or equal than heat capacity of stream 11:

$$F_{h,2,a}c_{p,h2,a} + F_{h,2,b}c_{p,h2,b} = F_h c_{p,h,2} \tag{25}$$

$$0 < F_{h,2,a}c_{p,h2,a} \,\&\, F_{h,2,b}c_{p,h,2,b} < F_c c_{p,c,1} \tag{26}$$

The networks are compared for two different criteria. The first one is the maximum energy recovery (left part of Table 2.7) and the other is the maximum heat transferred per unit of area, which results in lower investment cots (right part of the Table 2.7). Together with the flow ratios and the amount of recovered heat, the heat exchanging area is given.

The direct match gains 89% of the recoverable energy. Seven of the networks systems (network 3 to 9) come to a higher energy recovery. Network 2 has a performance equal to that of the direct match.

However, almost all favourable networks need a significant larger heat exchanging area. For example, in network 5 and 9, 98-99% of the recoverable heat is gained but the required heat exchanging area increases with 50%. Optimization of these networks with respect to heat transfer per unit of area (right part of the Table 2.7), gives a slightly lower amount of recovered energy.

Network 3, 6 and 7, achieve heat recovery in the range of 92-99% of total recoverable energy, but the total heat exchanging area is large (two and a half times compared to network 1) and affects the investment costs. However, optimisation of heat transfer per unit of area yields for network 7 a significant lower surface (even lower than the direct match), but now is the recovered heat comparable to the direct match.

For maximum heat recovery and the lowest number of exchangers, network 4 is preferred above networks 5, 8 or 9 due to the lower number of heat exchangers for the same performance.

Table 2.7: Network performance for maximum energy recovery and maximum energy transfer per unit of area

Network	Maximum Energy Recovered				Maximum *Q/A*			
	Heat capacity flow 10a/10b kJ/°C hr	Heat Recovered kJ/hr	A_{ec} m²	Q/A_{exc} kJ/m²hr	Heat capacity flow 10a/10b kJ/°C hr	Heat Recovered kJ/hr	A_{ec} m²	Q/A_{ec} kJ/m²hr
1 (direct match)	-	21149	13.20	1602.61		21149	13.20	1602.61
2	107.20/113.75	21149	19.74	1071.31	107.20/113.75	21149	19.74	1071.31
3	197.20/23.75	21927	34.74	631.26	107.20/113.75	18395	15.08	1219.66
4	197.20/23.75	22733	19.35	1174.60	98.20/122.75	22225	17.05	1303.21
5	197.20/23.75	23533	19.48	1208.32	98.20/122.75	22675	15.92	1424.28
6	197.20/23.75	21927	34.89	628.27	98.20/122.75	20048	18.37	1091.18
7	197.20/23.75	23673	35.65	664.10	62.20/158.75	21080	12.90	1633.47
8	197.20/23.75	23704	19.37	1223.94	107.20/113.75	23106	17.41	1326.86
9	197.20/23.75	23773	19.33	1229.83	98.20/122.75	23293	17.20	1354.54

3.4. Network design and flexibility

The network aims to recover maximum energy by using the hot and cold stream resources with minimum utility and low number of heat exchangers. The network is also expected to be flexible to deal with different operation conditions of the sources and targets (i.e. other temperature and flow levels). The suggested solutions, given in Appendix 2.2, make it possible to operate at different levels for drying conditions.

Network 5, 6, 8 and 9 (see Appendix 2.2) can be used to recover energy for various targeted drying temperatures. If a lower drying temperature reduces the heat demand of the heater between adsorber and dryer, other heat recovery units still will use the energy. In contrast, for networks 1, 2, 3, 4 and 7 the use of lower drying temperatures will result in extra energy loss. Here the remaining heat from the hot stream is not used in other heat exchangers. Network 1 is a clear example, if the temperature of cold 2 is 51.6°C (directly fed from adsorber to dryer), the hot stream 2 is not recovered.

4. Discussion

4.1. Heat exchanger selection

Network 1, 4, 5 and 9 have the best characteristics in heat recovery and the required heat exchanger (see Table 2.7). Combination with the criterion of flexibility network 5 and 9 remain. Specifications of these two networks with respect to the hot and cold streams that leave the networks are given in Table 2.8. In this table "Utility" presents the additional heat requirement to reach the target conditions in the drying system.

Table 2.8: Condition of each stream leaving the network and total required utility

Network	Hot 1 °C	Hot 2 °C	Cold 1 °C	Cold 2 °C	Cold Utility kJ/hr	Hot Utility kJ/hr
5	45.4	50.83	61.41	70	1676	48613
9	61.16	47.09	62.59	70	1436	48377

Network 5 and 9, give a cold 2 stream that matches directly to the required target temperature. These networks are able to reduce the temperature of hot 2 below 55°C, which is close to the target value of 45°C. So a minimal cooling with cold air is necessary.

The zeolite dyer system with energy integration needs around of 48500 kJ/hr, which contributes in the reduction of used energy (see Table 2.8). Compared to conventional dryer that uses 55050 kJ/hr (as presented in Table 2.2), the zeolite dryer yields 12% higher energy efficiency. Calculation results (not given) show also that with increasing moisture content of the ambient air, the improvements increase.

4.2. Variation of drying temperatures

Table 2.2 shows that the required energy decreases for lower drying temperatures. Here, the energy consumption of the integrated zeolite dryer is evaluated and compared to conventional dryer for different drying temperatures. The calculations were done for network 9 because of its high degree of energy recovery and flexibility. The results are presented in Table 2.9

The total energy recovery (except for total recycle), in the range 20700 to 23773 kJ/hr, corresponds to energy savings of 12 to 14% compared to a conventional dryer. The remaining heat in the exhaust air (hot 2) and zeolite stream (hot 1) cannot be reused further in the drying system. At a temperature of 51.6°C the air preheating unit does not need additional heat. When a total recycle is applied, the reduction of energy is also significant compared to that of a conventional operating at the same conditions: the heat required is reduced with 18%.

The results of the calculations indicate that at the lower drying temperature, and for the total recycle, the heat exchanger area required increases significantly to recover the heat. In addition, for these operations, the air fed to the dryer does not require additional energy and now hot 2 is maximally recovered for cold 1. As an alternative, exhausted energy can be used in other parts of the production plant (e.g. steam boiler).

Table 2.9: Maximum heat recovered at various temperature dryer conditions using network 9

Temp. Condition °C	Maximum Energy Recovered				Total Q required with recovery kJ/hr	Q Conventional Dryer kJ/hr
	Heat Capacity Flow 10a/10b kJ/°C hr	Heat Recovered kJ/hr	Area m^2	Q/A kJ/m^2hr		
70	197.20/23.75	23773	19.33	1229.83	48377	55050
60	197.20/23.75	21782	26.10	834.67	40850	46746
51.62	197.20/23.75	20070	36.03	631.26	34662	40389
Air recycling						
71.22	205.07/23.90	17777	36.47	487.46	46287	56300

5. Conclusions

The simulation calculations show that for medium temperature drying (50-70°C) of food products, a direct zeolite drying system with partial air recycle cannot compete with a conventional dryer. The main reason is the high energy content in the off-gas of the zeolite regeneration system. However, the energy in the off-gas can be recovered, and then the zeolite drying system is more energy efficient than a standard dryer.

For the three options for heat recovery the following conclusions were made:

– Direct use of the off-gas for a steam or power generation unit elsewhere on the plant. This option is most efficient and energy consumption is 25-30% below that of a conventional dryer.

– A direct match of the off-gas and hot zeolite for heating the drying air and regeneration gains 89% of the recoverable heat and makes the zeolite system 10% more efficient than a conventional dryer. However, changing the operation condition for drying affects the degree of heat recovery.

– Pinch based process integration with a heat exchanger network gives several solutions. Now, up to 99% of the recoverable heat is gained and compared to the conventional dryer the efficiency of the zeolite dryer increases up to 12-14%.

– For lower operating temperature the efficiency of the integrated zeolite dryer increases slightly.

– A total recycle of drying air gives another step in the efficient improvement. The total of heat required in this system is 18% below that of a conventional dryer.

– In the considerations for the choice of a network it is important to take the flexibility of the heat exchanger network for drying at different temperature levels into account

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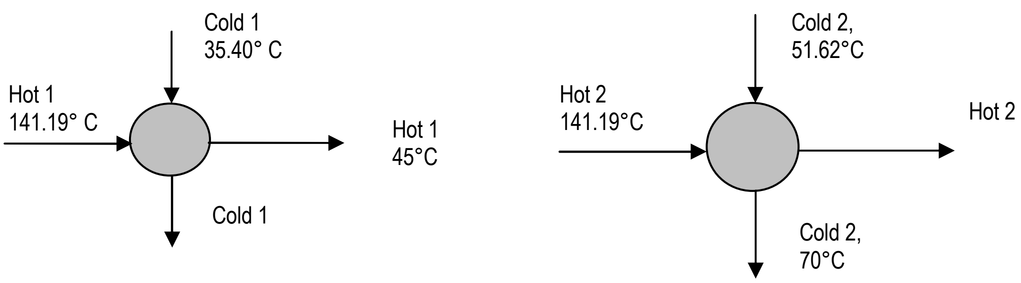
Appendix 2.1

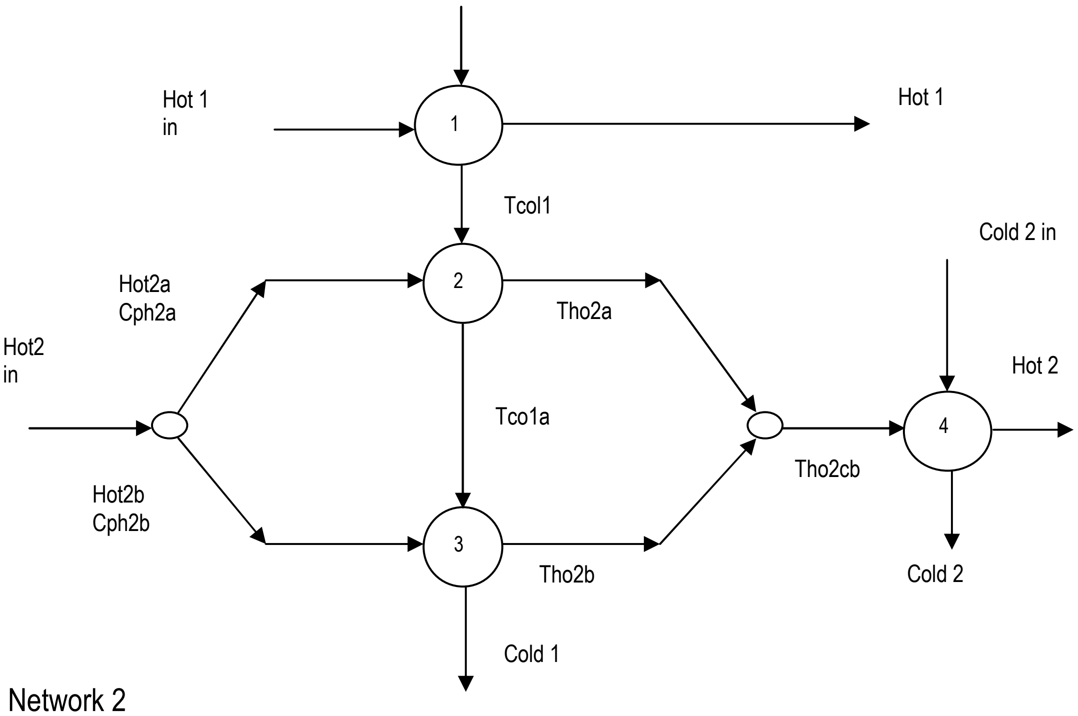
Table A1-1: Applied values for constants and process conditions

Parameter	Value
Flow of wet air to adsorber (kg/h)	1000
Air humidity to adsorber (kg water/kg dry air)	0.01
Temperature of air to adsorber (°C)	25
Humidity of air after adsorber (kg water/kg dry air)	0.001
Moisture at zeolite to adsorber (kg water/kg dry material)	0.000
Temperature of zeolite to adsorber (°C)	35
Moisture at zeolite after adsorber (kg water/kg dry material)	0.200
Temperature of wet product (°C)	25
Moisture of wet product (kg water/kg dry matter)	2.333
Moisture of dry product (kg water/kg dry matter)	0.110
Relative humidity of air after dryer (%)	40
Wet bulb temperature of dryer(°C)	24.5
Temperature of air to dryer (°C)	70
Temperature of air to regenerator (°C)	300
Operational pressure (bar)	1
Specific heat of dry air (kJ/kg °C)	1
Specific heat of water vapor (kJ/kg °C)	1.93
Specific heat of zeolite (kJ/kg °C) [6,7]	0.836
Specific heat of water (kJ/kg °C)	4.180
Specific heat of dry product (kJ/kg °C)	2.20
Heat of water adsorption/desorption (kJ/kg) [6,7]	3200
Heat of water evaporation (kJ/kg)	2500

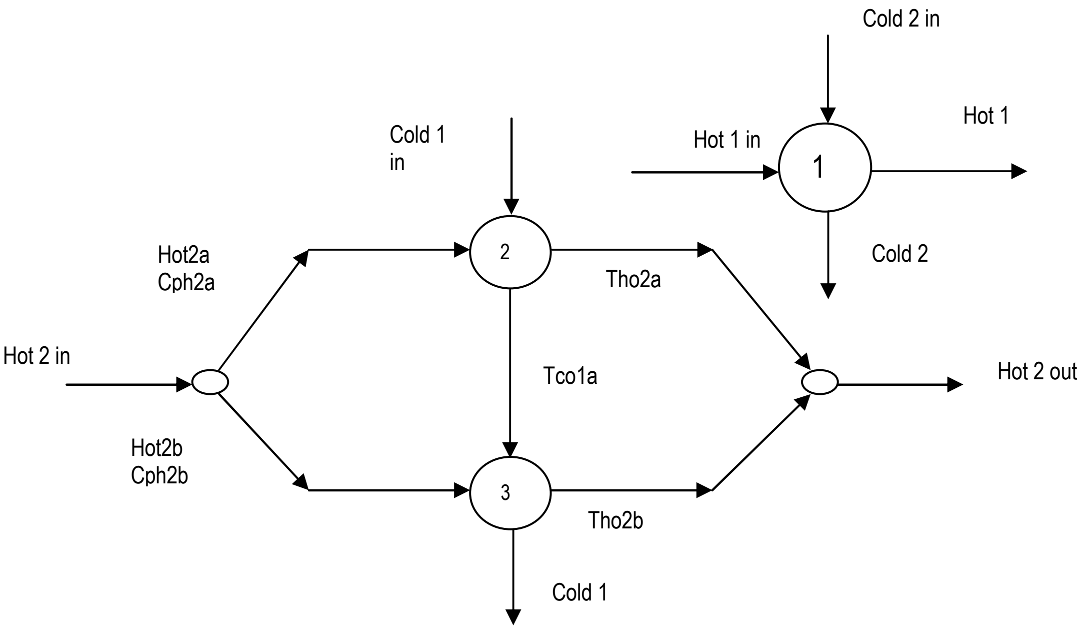
Appendix 2.2: Network systems



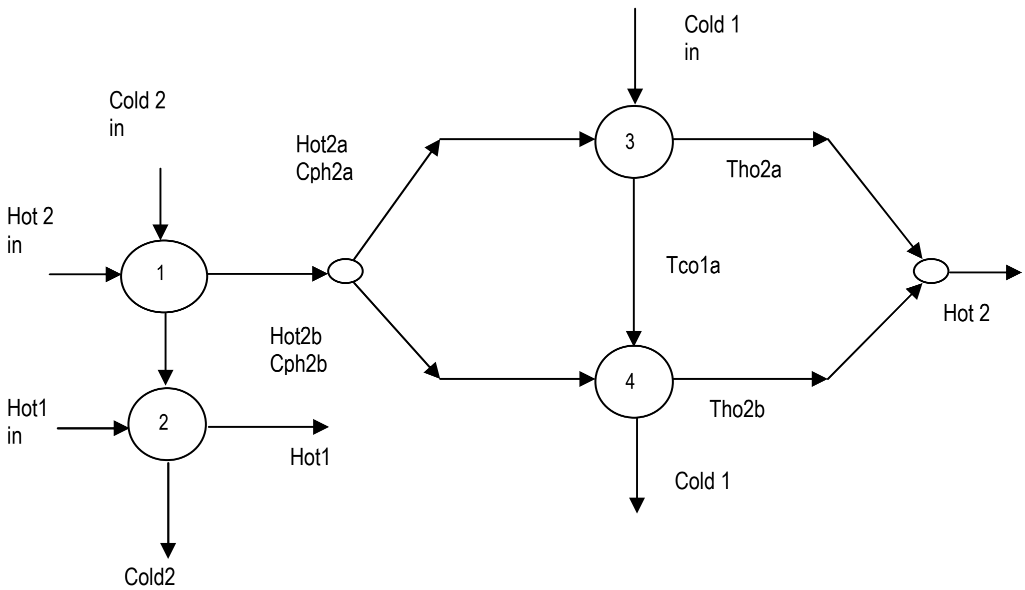
Network 1



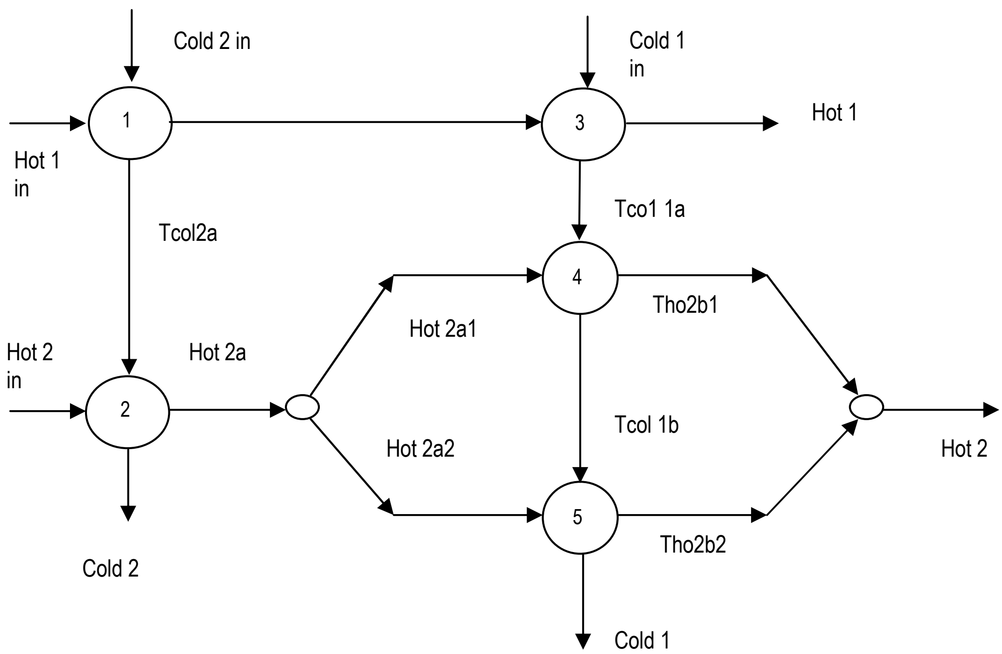
Network 2



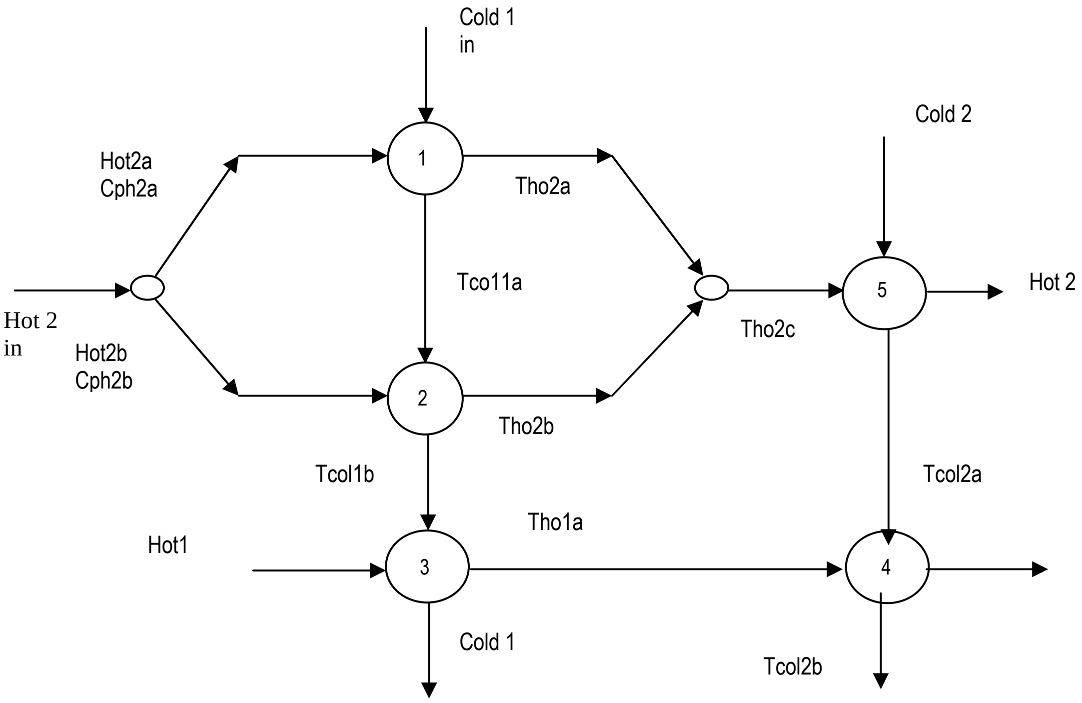
Network 3



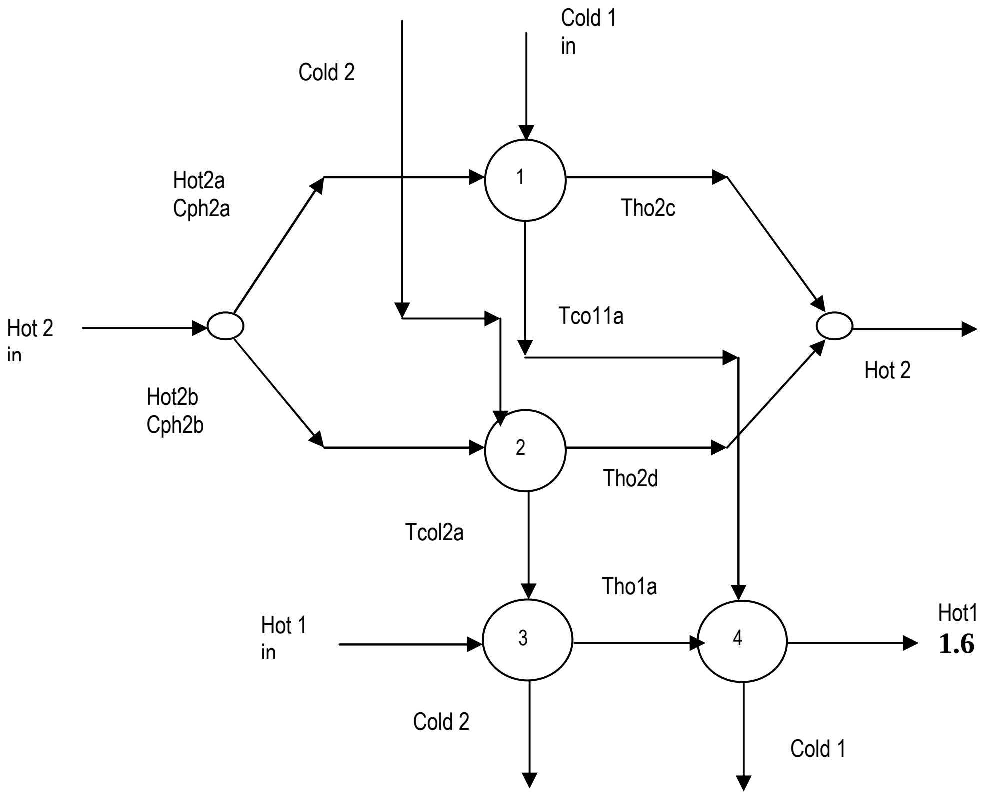
Network 4



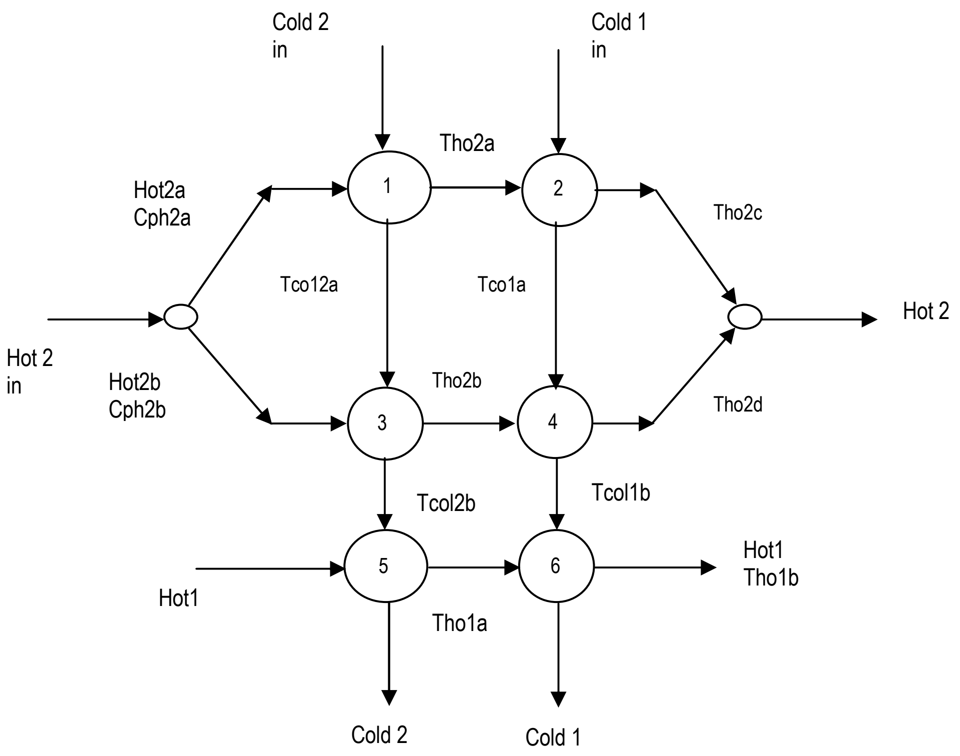
Network 5



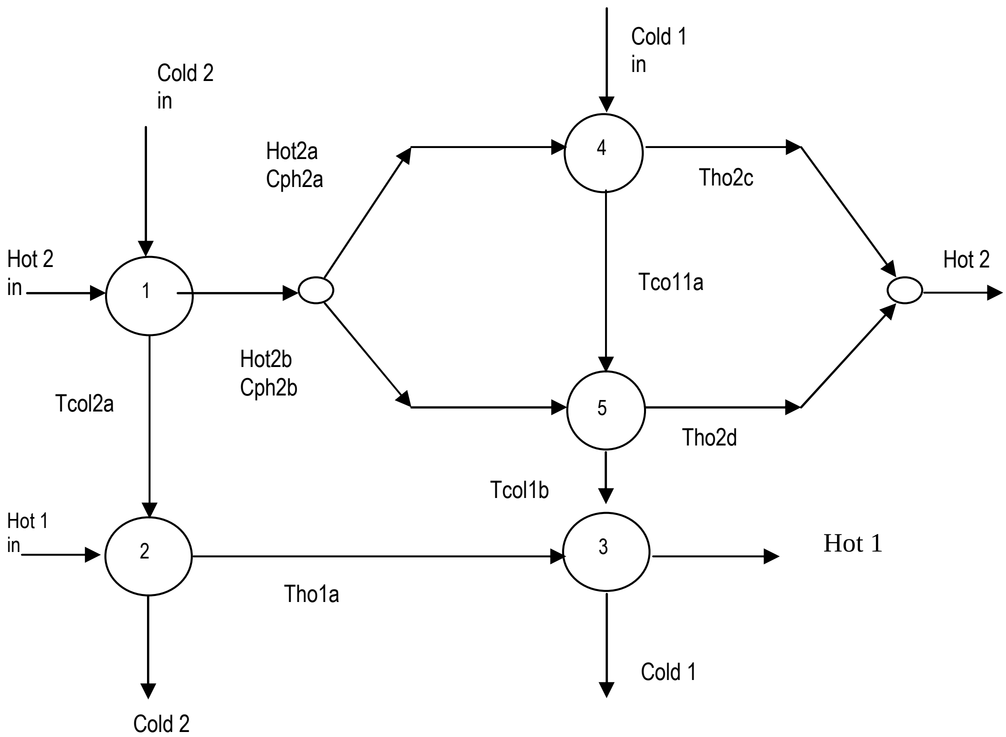
Network 6



Network 7



Network 8



Network 9

Chapter 3

Multistage Zeolite Drying for Energy Efficient Drying

Published in: Drying Technology **2007**, *25*(6), 1053-1067

Abstract

This work discusses the potential of three multistage zeolite drying systems (counter, co, and cross-current) with a varying number of stages. The evaluation showed that for 2-4 stages with heat recovery the efficiency of the systems ranges between 80-90%. Additionally, by introducing a compressor, the latent heat in the exhaust air from the regenerator is recovered and used to heat the inlet air for an additional drying stage. As a result, for the counter-current drying system and compressor pressure 1.5-2 bar, a maximum energy efficiency of 120**%** is achieved which results in halving the energy consumption compared to conventional drying systems.

Keyword*:* Drying, Efficiency, Multistage, Heat recovery, Zeolite

List of Symbols

c_p	specific heat	(kJ/kg°C)
E	energy flow	(kJ/hr)
F	flow of material	(kg/hr)
F_g	flow of wet gas/wet air	(kmole/hr)
H	flow of enthalpy	(kJ/hr)
ΔH_v	latent heat of water evaporation	(kJ/kg)
ΔH_{ads}	heat of water adsorption	(kJ/kg)
k	compressibility coefficient of gas	
M	condensation rate of water	(kg/hr)
P	pressure	(bar)
P/A	product to air ratio (wet basis)	(kg/kg)
Q	energy exchange with external utility	(kJ/hr)
R	gas constant	(kJ/kmole K)
η	energy efficiency	(%)
RH	relative humidity	(%)
T	temperature	(^{o}C)
X	water content in solid material	(kg water/kg dry material)
Y	moisture content in air	(kg water/kg dry air)

Subscripts

a	dry air	*ad*	adsorber	*ads*	adsorption
c	cold stream	*co*	cooler	*cmp*	compressor
d	dryer	*des*	desorption	*ex*	exhaust
evap	evaporation	*h*	hot stream	*he*	heater
in	inlet	*int*	introduced	*min*	minimum
out	outlet	*p*	dry product	*pre*	pre-heater
rec	recovery	*reg*	regenerator	*req*	required
sat	saturated	*t*	total	*trns*	transfer
v	vapour	*w*	water	*wa*	wet air
wp	wet product	*z*	dry zeolite	*i,j*	stream number
n, m	total number				

1. Background

Zeolite drying systems have potential to increase the energy efficiency (i.e. total energy required for evaporation of water divided by the consumed energy) for low and medium temperature drying of food and other heat sensitive products. The principle of zeolite drying is based on the removal of the water from the fresh air before feeding to the dryer. At the same time the air is preheated due to the release of adsorption heat. As a result of these effects the driving force for drying is enhanced, the required energy is reduced, and also a reduction of drying temperature is possible. A preliminary evaluation[1] showed that a single stage zeolite drying system can improve the energy efficiency with 10-18% in comparison to a conventional dryer. Furthermore, the air flow required to dry the same amount of product is lower and might result in smaller dryer equipment.

The disadvantage of zeolite drying is the high energy consumption and the high temperature needed in the regenerator to release the water from the saturated zeolite. It limits the improvement of the overall energy efficiency. For example, the release of 1 kg of water from a zeolite type 13X, requires 3200 kJ. The release of water improves with increasing temperature[2] and thus high regeneration temperatures are required. For 13X-zeolite temperatures above 120°C are preferred. Additionally, to make the zeolite drying system energy efficient 2-4 heat exchangers are required to recover the energy in the exhaust air from the regenerator.[1] In practice, it results in an increase of investment costs that may reduce the feasibility of the system. Hence, improvement of energy efficiency is still a main issue to make a zeolite dryer system competitive.

A promising alternative to improve the energy efficiency is the use of a multistage zeolite drying system, where the product contacts zeolite dehumidified air in several units. Such system consists of a number of dryers, adsorbers and regenerators in series. Before the first passage in the first stage, the air is dehumidified. The exhaust air from the first dryer stage passes an adsorber with zeolite which removes the water and increases the temperature due to the release of adsorption heat. Then the air is fed into the second dryer stage etc. In this system the energy content of the exhaust air is not lost, but upgraded and reused for drying at a higher temperature and lower water content. The multistage drying results in a higher product capacity and higher energy efficiency. Figure 3.1 part A, gives a schematic overview of the psychometric chart for the zeolite dryer concept for a single and a multistage system, and shows that the drying temperatures in the multistage system are lower. In this schematic presentation the water adsorption from the air by the zeolite is about 75%, but in practice it can go up to 95%.

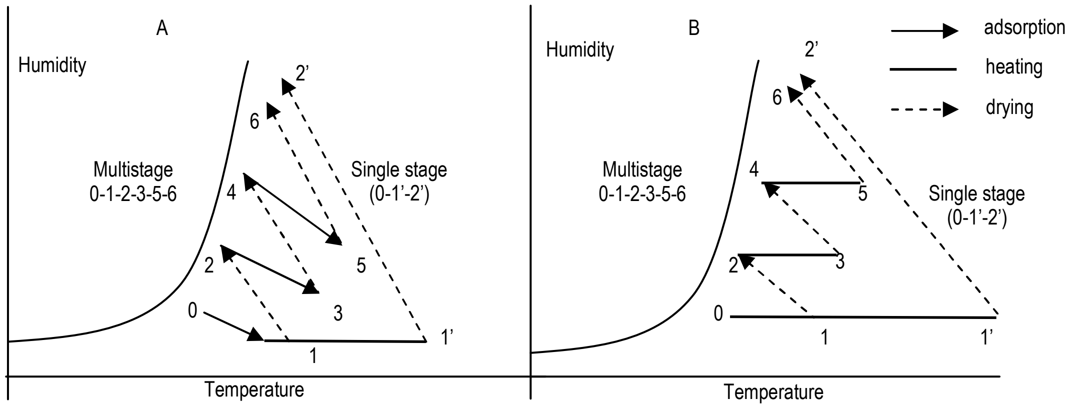


Figure 3.1: A. Comparison of a single stage and a multistage zeolite dryer. B. Comparison of a single stage and multistage conventional dryer.[3,4] Fresh air is fed to the system at position 0. After adsorption and/or heating position 1 is reached for the multistage systems and 1' for the single stage systems. From this point the multistage systems continue with drying, adsorption or heating along the path 1-2-3 etc until 6. The single stage system continues to 2'.

The concept of multistage drying, where the energy of the exhaust air is reused has been proposed for non-zeolite drying systems.[3,4] To get a better driving force in the next stage exhaust air from a stage is re-heated to lower the relative humidity and to increase the temperature. Figure 3.1 part B represents the comparison of a single stage and a multistage conventional dryer.[3,4] Important advantage of this multistage system is that high air temperatures in inlet air are avoided and the air flow is below that for a standard dryer.

The multistage dryer system provided important benefits compared to conventional single dryer systems.[5] The evaluation showed that the operational cost of the multistage dryer competes with a single-stage dryer at longer amortization time.[4] The best improvement of energy efficiency was achieved at operational temperatures below 100^{o}C for 2-4 drying stages with around 10% energy saving but the improvement is not significant for high temperature drying.[6]

According to these results, it can be concluded that multistage drying has potential to improve efficiency and to reduce operational costs. The disadvantage of the conventional multistage drying system is that the water content in the air increases in each drying stage. To compensate for this effect the temperature in the sequence of drying stages has to be increased. For heat sensitive products such as herbal medicines and food, the increasing temperature and drying time are not desirable since it reduces product qualities as color, essential oil content, structure (e.g. starch) and chemical composition.[7] Furthermore, the multistage conventional dryer cannot improve the efficiency in high temperature drying significantly.[6]

These limitations can be overcome by using a multistage zeolite drying system. Here the water in the humid air from each drying stage is adsorbed by contacting zeolite, while at the same time the temperature increases. The driving force after passing the zeolite bed increases so that drying can take place at moderate temperatures. Although the drying process becomes efficient by using the zeolite, regeneration can still limit the gain in efficiency. The objective of this paper is to evaluate multistage zeolite drying systems together with the regeneration systems and additional heat recovery. Cross, counter and co-current drying are considered and all the systems are equipped with heat recovery units. The energy efficiency, product to air ratio, and complexity of the process based on the number of stages are considered as performance indicators in the evaluation.

2. Methodology

2.1. Process Objective

The aim is to evaluate the performance of multistage zeolite drying for heat sensitive products with respect to the following criteria:

1. energy efficiency,
2. product to air ratio, and
3. complexity of the process.

As the energy consumption of drying is high and because the costs of energy are expected to increase in the next decades, improvement of energy efficiency is considered as the main indicator. The product to air ratio is a measure for the amount of air required to dry the product and affects both the size of equipment and energy required to heat the air. Complexity is important since it will affect the investment cost to establish the system.

2.2. Process configurations

Three configurations to improve the performance of zeolite dryers are considered: counter-current, co-current and cross-current (see Appendix 3.1). In counter-current multistage zeolite drying (see Figure A1-1, Appendix 3.1) the product is fed at the last stage of the dryer series. Meanwhile, after passing an adsorber with zeolite, the inlet air is used for the first drying stage. The humidified air leaving this stage contacts the following adsorber where the humidity decreases and the temperature increases. Then the air is fed to the next drying stage. This process is repeated several times. At each stage the zeolite is continuously regenerated by exchange of zeolite between adsorber and regenerator. The exhaust air of each regenerator is reheated and used for the next regeneration unit. In this system, the dried product is obtained in the first stage, while air leaves the system in the last dryer stage.

Conversely, at the co-current dryer, which is given in Figure A1-2, Appendix 3.1, after passing the first adsorber the inlet air contacts the inlet product directly. Before entering the next step, the humidified air passes the following adsorber to reduce humidity and increase temperature. Mass and heat transfer are enhanced by increased temperature and humidity difference between product and air, which results in an improved drying rate. The regeneration units are connected in a similar way as in the counter-current system.

In the cross-current zeolite dryer all drying stages are fed with fresh material, see Figure A1-3 Appendix 3.1. The product is dried in the stages. The exhaust air of each stage is fed to a next adsorber, and due to the amount of water released from the product in previous drying stage, the temperature of the air in the adsorber may be above the drying temperature in the previous stage. As a result, in the sequence of adsorbers the air temperature rises and the capacity in sequence of stage increases.

2.3 Heat recovery

Heat recovery using a minimum temperature difference of 10°C as driving force, was introduced to reuse the enthalpy content in the exhaust air from the last regenerator and in the zeolite flows leaving every regenerator.[1] Heat recovery is based on process integration as formulated by Linnhoff[8] and is directed on the efficient use of energy for drying.[1,9]

In the zeolite dryer, the enthalpy of the exhaust air from the last regenerator (high temperature and vapor content) can be recovered (e.g. to heat the fresh air charged to the first regenerator). The high temperature provides sensible heat, while the vapor provides latent heat of condensation. Moreover, the regenerated zeolite has to be cooled before feeding back to the adsorber, and this enthalpy flow can be utilized too. Hence, there are two kinds of streams in the system namely a hot stream that has to be cooled and cold stream that has to be heated up as depicted in Table 3.1.

Table 3.1: Summarizing hot and cold streams

Type	Stream	T (source) °C	T (target) °C
Hot Stream			
Hot 1	Zeolite from regenerator 1,2,..m	120-140	35[1]
Hot 2	Exhaust air from regenerator, m	120-140	45[1]
Cold Stream			
Cold 1	Air entering regenerator 1	30*	300
Cold 2	Air entering regenerator 2	160-170	300
Cold n	Air entering regenerator n	140-150	300
Cold n+1	Air exiting adsorber 1	50-60	70

The streams contact each other in a heat exchanger network as presented in Figure 3.2. This system aims to reduce the total heat required in the system and increases the total efficiency by a lower amount of energy for the heating and a lower amount of cold utility for cooling. Due to the small zeolite flow (ratio zeolite flow and air flow is 1:20), the zeolite flows from each regenerator are mixed in one stream (hot 1) to minimize the number of heat exchangers. The amount of heat recovery is estimated by summing the heat transferred in each heat exchanger including sensible and latent heat, see equation 1 and 2.

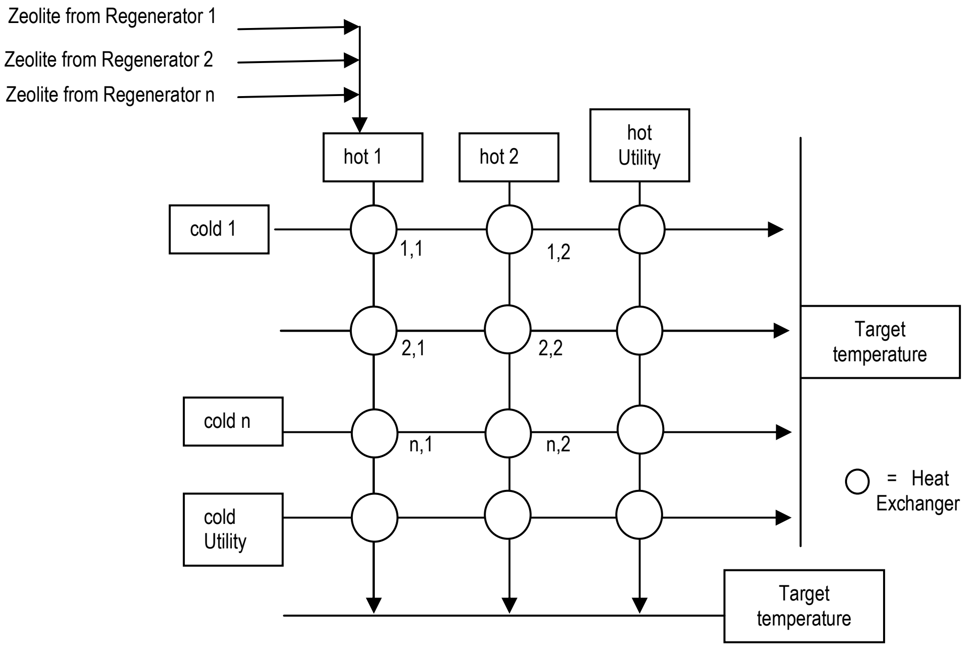


Figure 3.2:Heat exchanger network

$$Q_{trns,i,j} = F_{h,i}^{j} c_{p,h,i}^{j} (T_{h,i}^{j} - (T_{c,i}^{j} + \Delta T_{min})) + M_{w,i}^{j} \Delta H_v \quad (1)$$

$$Q_{rec} = \sum_{i=1}^{n} \sum_{j=1}^{m} Q_{trns,i,j} \quad (2)$$

2.4. Model Development

All the systems are simulated using steady-state mass and energy balance equations for each operational unit as given in Figure 3.3. The model is developed by considering several assumptions: the air is an ideal gas, relative humidity of the exhaust air from each dryer stage is 40%, the process is adiabatic and is considered as a well-mixed system, the efficiency of zeolite to adsorb water is 90% and the physical properties (specific heat, density etc) are constant. The models of each unit given in previous work of Djaeni et al[1] are presented in Appendix 3.2. The models are based on the dry zeolite, air and product flows.

The values of the input variables, the used constants, and the stream notations for the calculations are given in Table A2-1, Appendix 3.2. The resulting output variables are calculated from mass and energy balances. These calculations are applied for each stage.

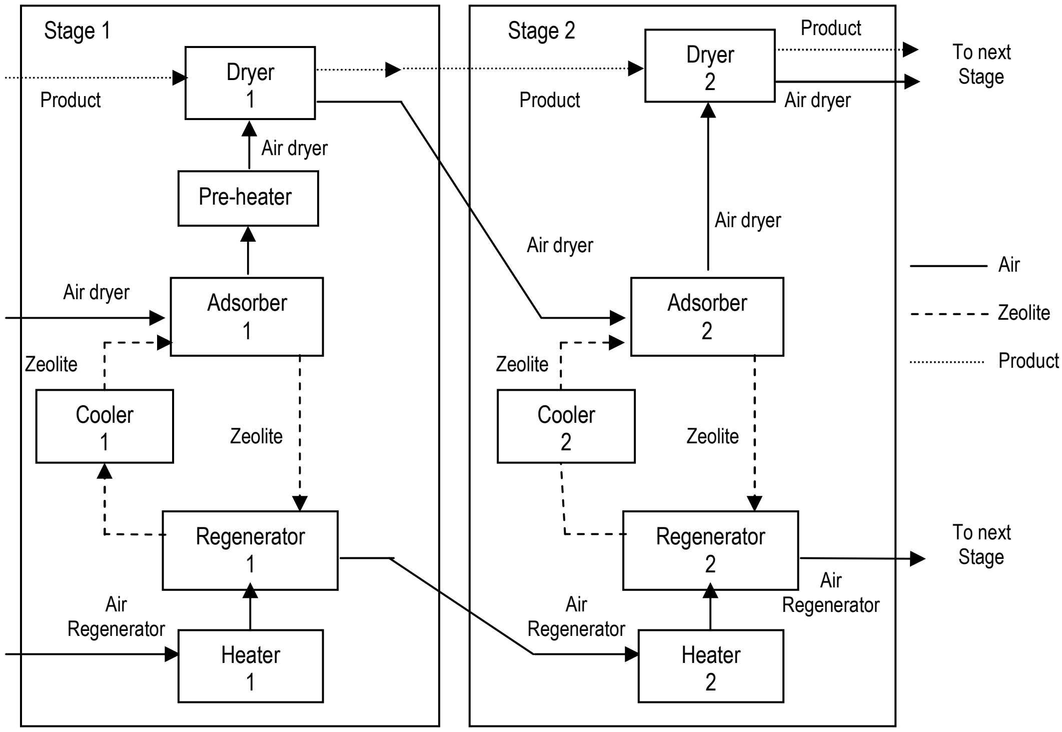


Figure 3.3: Operational units and their interconnection in co-current multistage zeolite dryer

2.5. Definition of evaluation criteria

The performance evaluation uses the following criteria:

a. Energy efficiency (%)

Energy efficiency is defined as the heat required for evaporating the amount of removed water divided by total of heat introduced to the system:

$$\eta = \frac{H_{evap,t}}{Q_{req}} 100\% \quad (3)$$

$$H_{evap,t} = F_{p,t}(X_{p,in,1} - X_{p,out,n})\Delta H_v \quad (4)$$

$$Q_{req} = Q_{int} - Q_{rec} \quad (5)$$

b. Product to air ratio

This indicator represents the mass efficiency of the used air. Higher air flows require more heating energy. Moreover, a higher product to air ratio can be profitable for the dimensions of the equipment.

The product to air ratio is based on the total flow of product entering the zeolite dryer system (see equation A2-17 to A2-19, Appendix 3.2).

$$(P / A) = \frac{F_{wp,t}}{F_{wa,t}} \tag{6}$$

c. Complexity of configuration

An increasing number of stages will make the system more complex since more operational units have to be used and the number of flows increases. The energy efficiency has to be weighted with the complexity. It is expected that by extending the number of stages, the efficiency will increase. However, at certain point the efficiency improvement is marginal while the complexity still increases.

3. Result and Discussion

Multistage drying enhances the drying efficiency. Nevertheless heat recovery remains also an essential step in improving the efficiency and both aspects have to be combined. In this section the advantages of the multistage system will be qualified first and then the possibilities to enhance the efficiency will be discussed in the following sub sections.

3.1. Basic results for multistage zeolite drying

Table 3.2 presents the results for the multistage drying systems. For all cases, extending the dryer system increases the efficiency and product to air ratio. Without heat recovery the efficiency achieves 67-72% at 4 stages (see column 6 row 5, 8, 11). The counter-current dryer achieves the highest performance. Furthermore, the product to air ratio in the counter-current is the highest which implies the most efficient usage of air. Without heat recovery the efficiency of counter-current dryer ranges from 59 to 72%, and becomes 80-90% with heat recovery using a heat exchanger network as presented in section 2.3. This achievement is significant compared to the single stage zeolite dryer with heat recovery which achieves a total efficiency of 70-72%.[1]

The other process configurations give different efficiency results. For the cross-current dryer, the air from the adsorber contacts always fresh product. The total product that is dried is the sum of each stage. The advantage of this configuration is that it can be composed easily since the stages are independent on the other stage. As a result every stage has the inlet fresh feed as independent variable that can be used to control the process. However, since the air conditions vary in each stage, the equipment size in every stage can be different.

In the co-current system, the input air contacts the fresh feed in the first dryer and both streams go in the same direction through the system. The driving force between product and air (temperature and humidity) decreases along the stages. As a result, more heat and air is required for drying. As given in Table 3.2, the product capacity and the efficiency of co-current dryer are the lowest.

In the counter-current dryer, the air and product flows are in the opposite direction; fresh product is contacted with the air in the last stage of adsorbers (see Figure A1-1, Appendix 3.1). The advantage of this system is the ability to use the air from last stage to preheat fresh product. Furthermore, the heat and mass transfer in every stage is enhanced which is reflected by the enhanced product to air ratio and energy efficiency. The efficiency of counter-current is the highest and goes up to 88%, for a three stage system with heat recovery.

In conclusion, the counter-current dryer is the most favorable alternative. The difference between a three and four stage system is moderate and will probably not justify the extended equipment costs.

Table 3.2: Performance of multistage zeolite dryer

Options	Stages number	P/A (kg/kg)	Heat supplied (kJ/hr)	Heat used (kJ/hr)	Efficiency without heat recovery (%)	Heat recovered (kJ/hr)	Efficiency with heat recovery (%)
Conventional Dryer	1	0.018	55050	35000	63.6	-	63.6
1-stage zeolite with heat recovery	1	0.021	72150	35000	48.6	23000	72
Cross-current	2	0.044	123644	73000	59.5	33022	80.5
	3	0.070	174213	112594	64.6	37998	82.6
	4	0.090	228627	155213	67.9	42856	83.5
Co-current	2	0.042	123644	70000	56.6	33472	77.6
	3	0.066	173094	110000	63.5	38461	81.7
	4	0.090	225618	150000	66.5	43271	82.2
Counter-current	2	0.044	123644	73000	59.0	32698	80.2
	3	0.070	168429	116000	68.8	36894	88.1
	4	0.095	218359	158500	72.5	42261	90.01

3.2. Heat recovery potential

The forgoing results show that the efficiency of the zeolite dryer is about 69% by using a three stage counter-current dryer without energy recovery. The energy efficiency for this system increases up to 88% by applying heat recovery. This achievement is significant compared to the performance of a single stage zeolite dryer, which is 72% with heat recovery or 49% without heat recovery.[1]

The drawback in the multistage dryer is the high energy content in exhaust air that leaves the regenerator and which is not yet fully reused (see Table A3-1, Appendix 3.3). The heat recovery system in section 2.3 (see also Table 3.2, section 3.1) uses the sensible heat in the exhaust air and it does not use the latent heat. To reuse latent heat, the exhaust air has to be cooled below its dew point temperature. It implies that the cold stream temperature must be below the dew point of exhaust gas.

For the three-stage counter-current dryer, the regenerator exhaust air temperature is 127°C with a dew point of 60°C and the vapour content of 0.155 kg water/kg dry air (see Table 3.3). In the three stage system there is only one cold stream having a temperature below 50°C i.e.; ambient air to regenerator 1 (see Figure 3.4).

Table 3.3: Stream condition in three stage of counter-current multistage zeolite dryer

Cold Stream	Temperature °C	Moisture (kg/kg)	Mass Flow (kg/hr)	Enthalpy Flow (kJ/hr)	Target Temperature °C & heat required kJ/hr
1. ambient to reg, 1	25.00	0.0100	250	12496	300 & 69383
2. reg 1 to 2	166.33	0.0460	259	73291	300 & 36024
3. reg 2 to 3	146.83	0.0939	271	101030	300 & 44785
4. ads to heater	51.62	0.0010	991	53679	70 & 18237
Hot Stream					
1. zeolite (reg. 1,2,3)	143.50	0.0000	179	21533	35 & -16821
2. exhaust air (regenerator 3)	127.45	0.1550	286	136924	45 & -81999

Note: reg. refers to regenerator stage (see also Appendix 3.3)

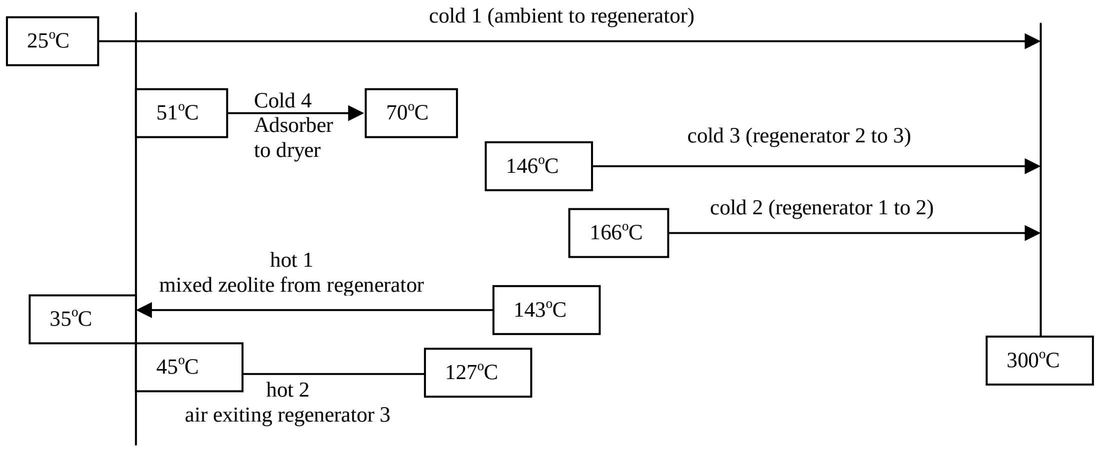


Figure 3.4: Relationship between hot and cold stream. The temperature values were obtained from design calculations

Figure 3.4 shows that cold 1 (ambient air) with a temperature source of 25°C can be heated up to 117°C (using hot 2) or 133°C (using hot 1) under the assumption of a minimum temperature difference of 10°C, while cold 4 (adsorber air) can achieve the targeted temperature. To heat cold 1, 2, and 3 to 300˚C further heating is needed. Heat recovery cannot be maximized since the cold and hot streams (except for cold 4) do not achieve the aimed temperatures. The total heat that can be recovered is 36000 kJ/hr or 37% from the total sensible heat of hot stream. If the latent heat of the air is also considered, the heat recovery is only around 25% (see Table 3.2 (column 7) and Table 3.3).

3.3. Enhancing heat recovery by increasing air pressure

An alternative to improve heat recovery is to increase the dew point temperature of the exhaust air to a higher level (e.g;>70°C) by increasing the air pressure. Therefore, the heat recovery unit is equipped with a compressor.[10] Now, three advantages are obtained:

1. utilizing more sensible heat from the exhaust gas,
2. enhancing the capability of the exhaust air to heat up cold streams, and
3. using latent heat in heat recovery

The energy consumption for an adiabatic compressor is given as:[11]

$$T_{cmp,out} = (T_{cmp,in} + 273.15)\left(\frac{P_{cmp,out}}{P_{cmp,in}}\right)^{(k-1)/k} - 273.15 \quad (7)$$

$$Q_{cmp} = \left(\left(\frac{P_{cmp,out}}{P_{cmp,in}}\right)^{(k-1)/k} - 1\right) RF_g k \left(\frac{T_{cmp,in} + 273.15}{k-1}\right) \quad (8)$$

Exhaust air recovery is presented in Figure 3.5 (P-T diagram) and Figure 3.6 (heat exchanger network). The exhaust air from the last regenerator, located at point 1 (temperature 127°C, partial pressure 0.20 bar, total pressure 1 bar), is adiabatically compressed till point 2 where both temperature and pressure are at a higher level. The compressed air is then cooled in the heat exchanger network. Firstly, the exhaust air transfers the sensible heat to a cold stream at constant pressure up to point 3. Then condensation takes place and the temperature of the exhaust air from the regenerator follows the condensation line towards point 4 (see also Figure 3.6).

The total efficiency is estimated for a compressor efficiency of 75%. The compressor energy is used to calculate the total heat recovery:

$$E_{req,cmp} = \frac{Q_{cmp}}{0.75} \quad (9)$$

$$Q_{rec,net} = Q_{rec} - E_{req,cmp} \tag{10}$$

$$H_{loss} = \sum_{j=1}^{m} H_h^j + Q_{cmp} \tag{11}$$

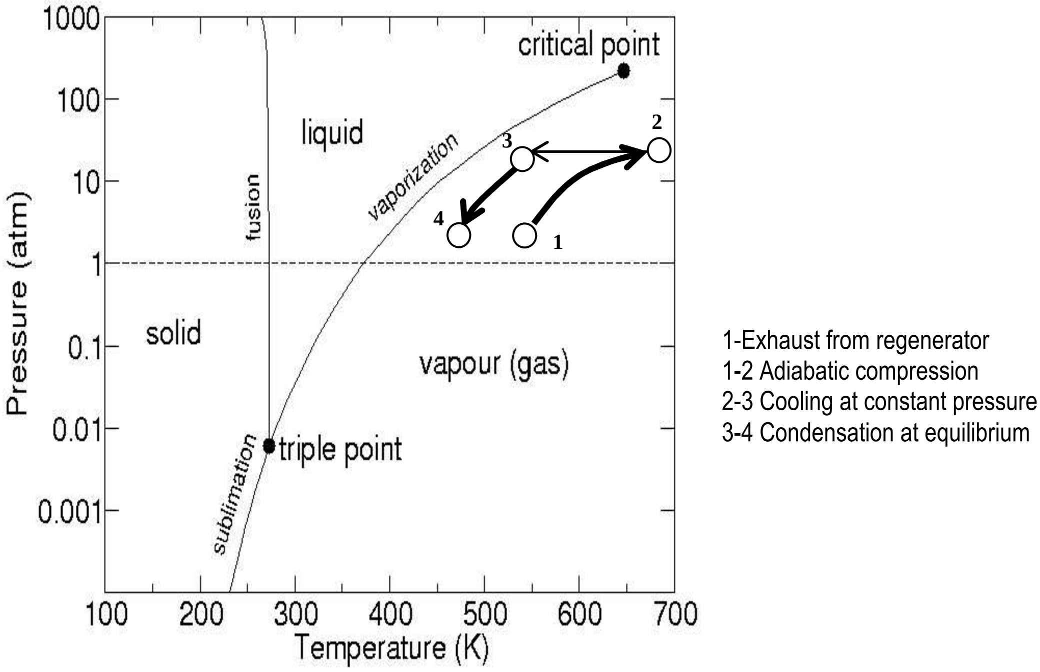


Figure 3.5: P-T diagram of exhaust water system with the partial pressure of vapor on the vertical axis[12]

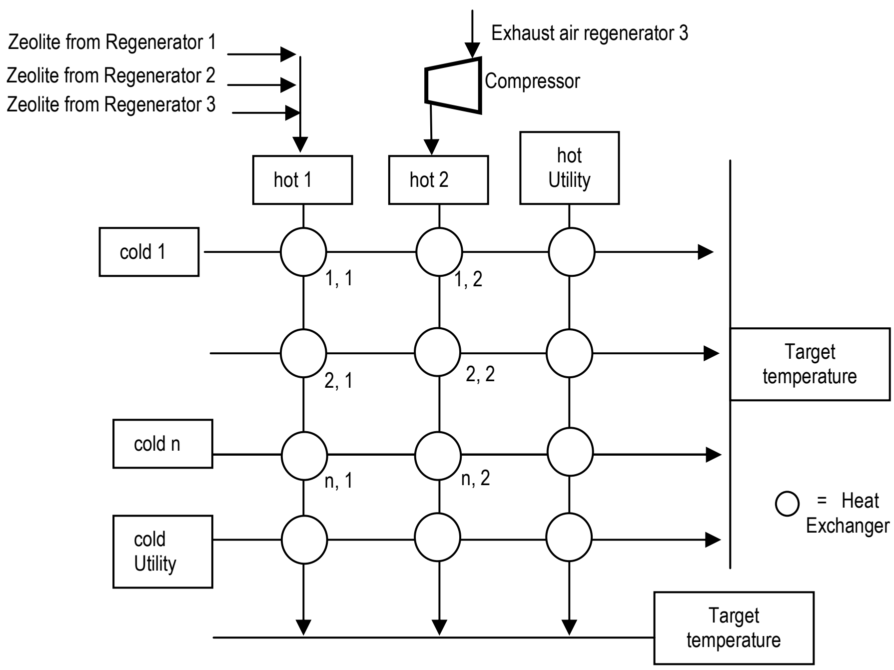


Figure 3.6: Heat recovery unit with compressor

The calculation results, given in Table 3.4 column 5, show that with the implementation of a compressor the recovered energy increases drastically. However, after counting the energy used by the compressor the improvement of energy efficiency is cancelled (see Table 3.4 column 7). The heat required to heat the cold stream from its source up to 10°C below the hot stream source is not enough. The reasons for the limitation are the low flows and high target temperature for cold 1,2, 3 (see Figure 3.4). Moreover, cold 4 (air from adsorber to heater) needs not much heat since this flow has to be heated up from 50°C to 70°C. As a result, the latent heat of vapor condensation in hot 2 cannot be exploited maximally. Thus, the use of a compressor in the system is not yet effective for the energy efficiency.

A meaningful alternative is, to reuse the heat in exhaust air from heat exchanger network to heat other cold streams in the plant, for example boiler water or ambient air for another dryer unit with a higher flow and lower temperature source. It is expected that in this way more heat can be recovered.

Table 3.4: The efficiency of a three stage counter-current multistage zeolite dryer at various pressures

$P_{cmp,out}$ Bar	Dew Point* exhaust air °C	H_{loss} kJ/hr (3)	$E_{req,cmp}$ kJ/hr (4)	Q_{rec} kJ/hr (5)	$Q_{rec,net}$ kJ/hr (5)-(4)	Efficiency %
1.00	60.20	158457	0	36894	36894	88.2
1.50	69.24	173815	20477	50558	30081	83.8
2.00	76.01	185842	36513	62911	26398	81.7
2.50	81.47	195877	49893	73216	23323	79.9
3.00	86.07	204564	61476	82138	20662	78.5
3.50	90.07	212270	71751	90053	18302	77.3
4.00	93.62	219225	81024	97132	16108	76.2
4.50	96.81	225585	89504	103556	14052	75.1
5.00	99.72	231457	97333	109488	12155	74.2
5.50	102.40	236924	104623	115010	10387	73.4

*Interpolated few Figs. 2-4, page 2-90, Perry[11]

3.4. Reusing the exhaust air for an additional dryer

Despite the results of section 3.3 there is still potential to recover the latent heat of the vapor in the compressed exhaust air from the heat exchanger network. It was realized by extension of the network with one extra heat exchanger to heat ambient air for an extra drying unit which can be used in the sequence of dryers of the multistage system. The temperature of the air for this extra unit is then increased from 25°C (ambient) to a temperature 10°C below the exhaust stream source (see section 2.3).

In Figure 3.7, the cold streams from the multistage zeolite dryer are matched with hot streams in the heat recovery unit. The exhaust air from the last regenerator (hot 2) is compressed before entering the heat recovery unit. The zeolite flow (hot 1) is recycled to the multistage zeolite dryer system. Finally, the exhaust air from the last regenerator (hot 2) contacts another cold stream of fresh ambient air in the additional heat exchanger before purging to environment. The total heat that can be recovered in the extra heat recovery unit is evaluated at various air pressures; see Table 3.5.

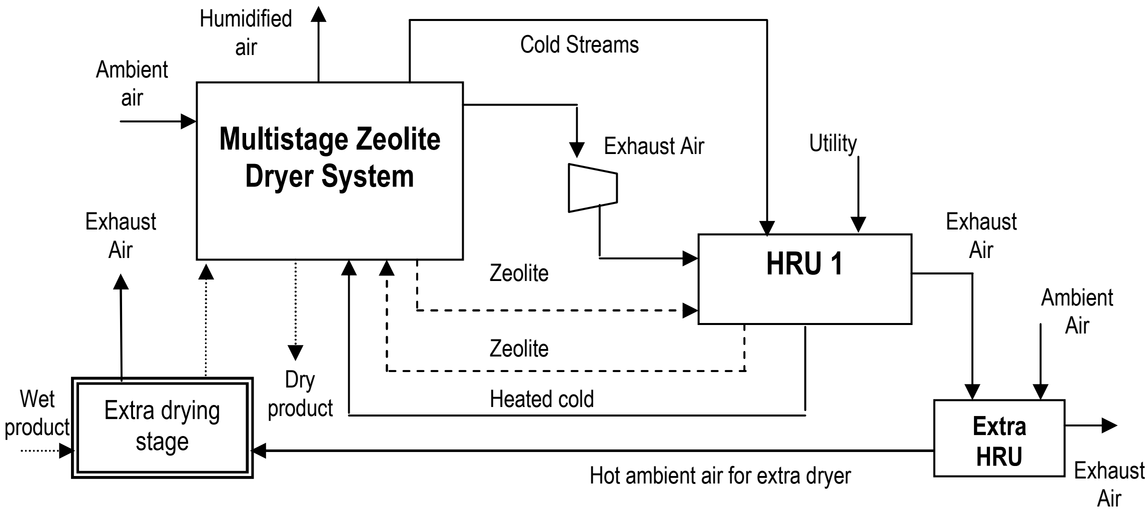


Figure 3.7: Extended drying system with one extra drying stage and one heat exchanger to maximize heat recovery

Table 3.5: Heat recovered for additional dryer unit

Exhaust air after HRU 1				Exhaust Air after extra HRU 45°C			Heat Recovered kJ/hr (4)-(7)
P bar	T source °C	Y kg water/kg dry air	Enthalpy kJ/hr (4)	P bar	Y target kg water/kg dry air	Enthalpy kJ/hr (7)	
1.0	63.35	0.1550	116311	0.9	0.0654	53017	63295
1.5	70.06	0.1550	118005	1.3	0.0421	38112	80358
2.0	76.44	0.1518	117680	1.7	0.0312	31119	87272
2.5	81.67	0.1491	117407	2.1	0.0248	27021	91288
3.0	86.03	0.1468	117142	2.5	0.0206	24327	93876
3.5	89.79	0.1450	116958	2.9	0.0176	22418	95739
4.0	93.11	0.1434	116840	3.3	0.0154	20994	97170
4.5	96.10	0.1420	116766	3.7	0.0137	19891	98312
5.0	98.81	0.1408	116705	4.1	0.0123	19011	99235
5.5	101.29	0.1397	116634	4.5	0.0112	18293	99974

Table 3.5 presents in the last column the total heat that can be recovered from the compressed air in the extra heat recovery unit (HRU). For the calculations it was assumed that the air was cooled down in a counter current exchanger to 45°C, which refers to previous work.[1]

The air flow from the HRU 1 was 247 kg dry air/hr and the water content of the air is around 0.150 kg water/kg air. The pressure drop over the extra heat recovery unit below 0.7 bar is acceptable.

The heat recovery potential increases with compressed air pressure due to the increasing amount of condensed vapor. However, to generate higher pressures more energy is used by the compressor (see Table 3.4). So there will be an optimum for the compressor pressure. If the additional dryer operates at 60% drying efficiency, the energy efficiency of the total system increases drastically (see Table 3.6). The total efficiency for all pressures exceeds 100% since the system exploits heat from the condensing vapor in regenerator exhaust air. An optimum efficiency energy efficiency of 120% is achieved at 1.5-2.0 bar. This result is obtained when the ambient air flow in the range of 2000-2300 kg/hr (wet basis) is heated to 60-65°C.

Table 3.6: Total energy efficiency with additional dryer

$P_{cmp,out}$ bar	Heat recovered from exhaust* kJ/hr (2)	Heat used in additional dryer kJ/hr (3)=0.6* (2)	Heat used in three stage zeolite kJ/hr (4)**	Total required with compressor kJ/hr (5)	New energy efficiency, % =100%*((3)+(4))/(5)
1.0	63295	37977	116000	131535	117
1.5	80358	48215	116000	138348	120
2.0	87272	52363	116000	142032	119
2.5	91288	54773	116000	145106	118
3.0	93876	56325	116000	147767	117
3.5	95739	57444	116000	150127	116
4.0	97170	58302	116000	152321	114
4.5	98312	58987	116000	154376	113
5.0	99235	59541	116000	156275	112
5.5	99974	59985	116000	158042	111

* values transferred from Table 3.5 last column ** initial design

4. Discussion

The efficiency of zeolite dryer systems is enhanced by using a multistage zeolite dryer system. The energy efficiency is affected by the number of zeolite drying stages and the use of a heat recovery unit. In a single stage zeolite dryer with a heat exchanger network for heat recovery around 25-30% from the total enthalpy in the regenerator exhaust air is recovered which leads to an efficiency of 72% (see Table 3.2). For a multistage zeolite dryer with heat recovery the efficiency goes up to 80-88%. To get this result, 4 additional heat exchangers are required.

A compressor offers the possibility to recover the latent heat in the regenerator exhaust air at temperatures in the range 50-70°C. Two options in using the compressor were evaluated.

1. Direct use for heat recovery in the multistage system
2. Using for heat recovery in an extended drying stage

For option 1, compressing the regenerator exhaust air improves the driving force for heat recovery; the temperatures of the exhaust air increases as can be seen in Table 3.5. For higher temperatures, the possibilities to heat cold air increase. At pressures above 2 bar, the exhaust air temperature is above that of all cold stream sources (see Table 3.7 and Table 3.3), and heat recovery can be maximized (see Table 3.4). However, taking the energy used by the compressor into account and by assuming a compressor efficiency of 75%, the final efficiency is not improved (see Table 3.4). Moreover, this approach requires more heat exchangers.

The compressor increases the dew point temperature of the air after the last regenerator. If the dew point temperature is high enough, then another cold stream can be heated. It is proposed to heat air for an additional drying stage and this solution resulted in an impressive increase of efficiency (see Tables 5 and 6). With increasing pressure more heat is recovered and the air temperature for the extra dryer stage increases (see Table 3.5). However, for pressures above 2.0 bar, the efficiency of the system declines due to the increasing energy consumption of the compressor. The optimum energy efficiency of 120% is achieved at 1.5-2.0 bar where around 70-75% of latent heat in the exhaust air is converted into sensible heat for an additional drying stage.

The results obtained for the multistage zeolite dryer configuration, heat recovery unit, and compressor application, are influenced by the assumed capacity of the process (flow of air and product). For other capacities, product and air conditions the process configuration has to be optimized in combination with the investment cost. The benefit of energy savings for the total operation has to be estimated for the other situations to evaluate the feasibility of the process alternatives. These are also dependent on the external factors such as equipment and fuel costs, operational and maintenance costs and also the value of dried product.

Table 3.7: The temperature of exhaust air from the compressor

Exhaust	$P_{cmp,out}$ **bar**	Q_{cmp} **kJ/hr**	$E_{,req,cmp}$ **kJ/hr**	$T_{cmp,out}$ **°C**
$T_{cmp,in}$=120.73 $P_{cmp,in}$= 1 bar	1.0	0	0	120.73
	1.5	15358	20477	169.11
	2.0	27385	36513	207.00
	2.5	37420	49893	238.60
	3.0	46107	61476	265.97
	3.5	53813	71751	290.24
	4.0	60768	81024	312.15
	4.5	67128	89504	332.19
	5.0	73000	97333	350.70
	5.5	78467	104623	367.91

5. Conclusion

Three multistage zeolite drying systems have been configured and evaluated in combination with heat recovery. The energy efficiency of such multistage system is higher than that of conventional drying systems and single stage zeolite drying systems. The efficiency increases with the number of stages. Generally, the multistage systems are most effective for 2-3 stages; above this number the energy efficiency improvement is marginal and probably not sufficient to justify the increase of system complexity. The counter-current dryer is the most efficient and achieves an energy efficiency of 88% for a 3-stage system.

Heat recovery is enhanced with the introduction of a compressor which increases the temperature of the zeolite regenerator exhaust air. As a result the possibilities to recover sensible and latent heat improves. Both aspects enhance the amount of recovered energy. However, it appears that the energy required for the compressor energy cancels the benefits.

The other way is to use the compressed air to heat up other cold streams. In this work air for an additional drying stage is heated up. It improves the energy efficiency up to 120%. In this case, the latent heat in the exhaust gas is used by vapor condensation. Although, increasing the exhaust air temperature and pressure gives more potential to recover latent heat, there is an tendency for an optimum efficiency at 1.5-2.0 bar.

In many industries the high energy consumption for drying process is regarded as a serious problem. In conventional drying systems with inlet air temperatures between 60 and 90°C the maximal efficiency is around 60-65%. The multistage drying system realizes an efficiency level of 110-120% for the same conditions. In other words the energy consumption is halved, which is regarded as a significant step ahead in saving energy.

Acknowledgement

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Appendix 3.1

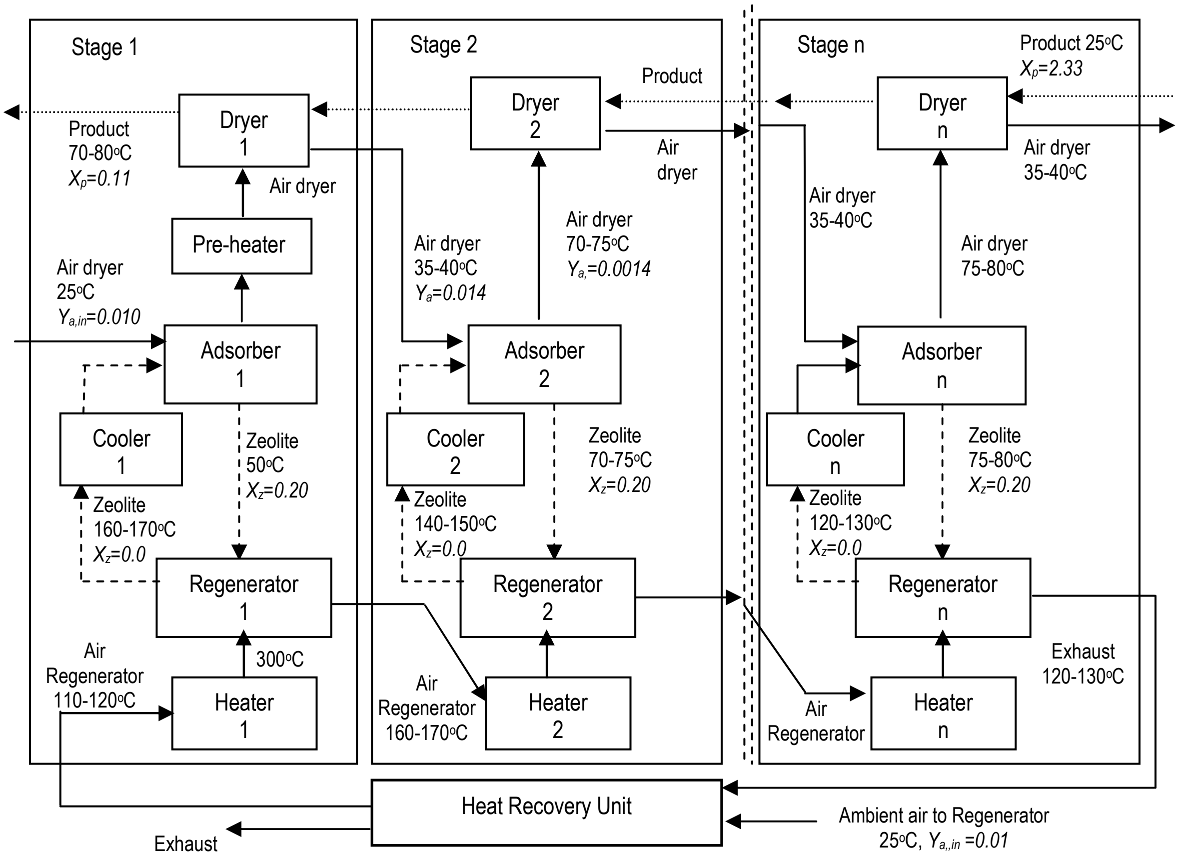

Figure A1-1: Counter-current zeolite dryer

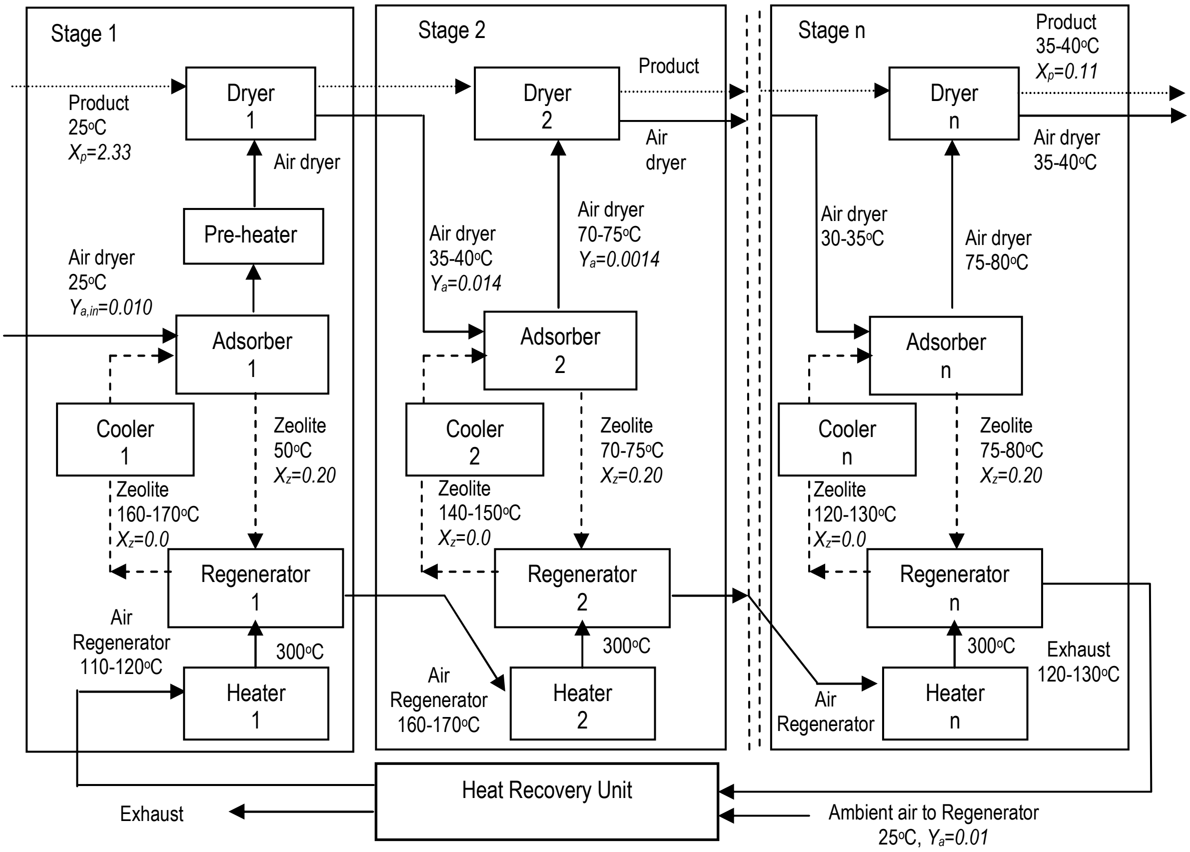

Figure A1-2: Co-current zeolite dryer

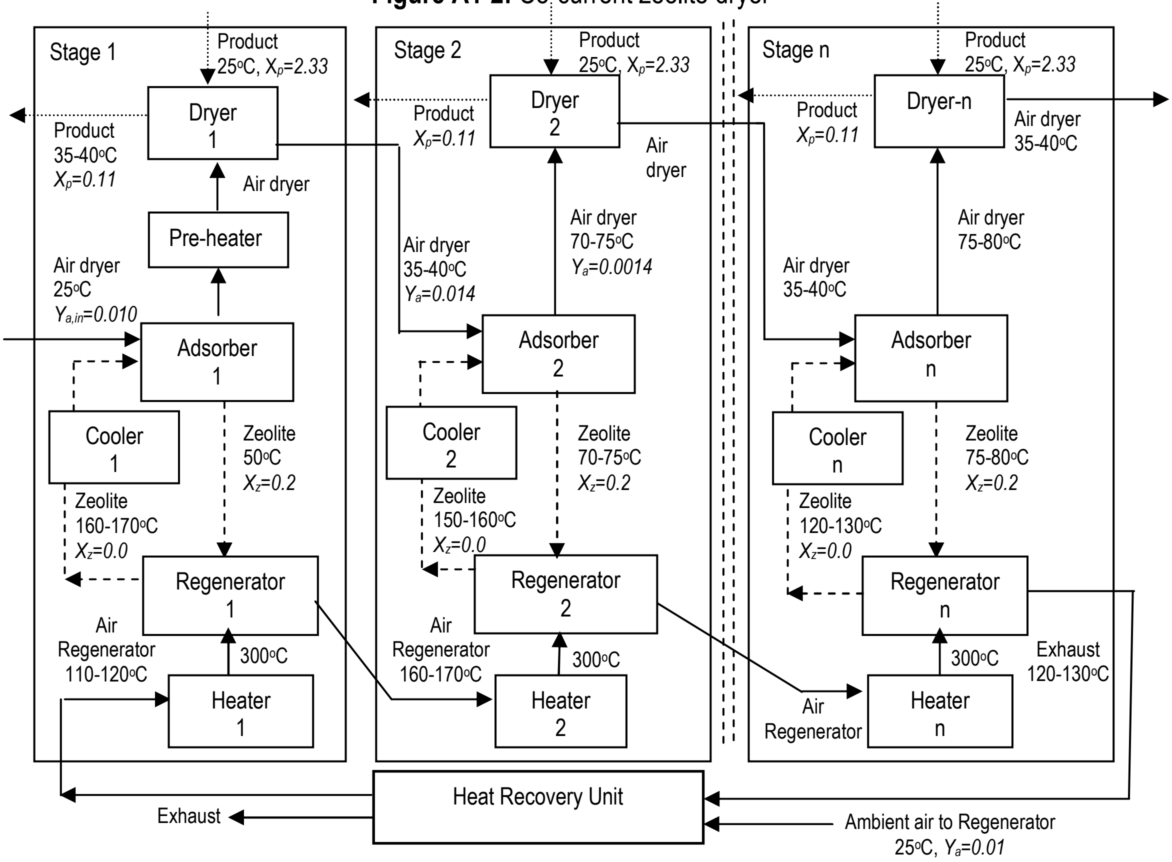

Figure A1-3: Cross-current zeolite dryer

Appendix 3.2

For the calculations both drying systems are split into subsystems. Steady-state models for the subsystems based on the conservation of mass and enthalpy are used. Assumptions for the calculations are:

- adiabatic processes for the subunits,
- constant physical properties (density, specific heat),
- pressure drop is excluded from the calculations,
- operational pressure 1 bar,
- well mixed subsystems,
- in all cases the exhaust air of the dryer has a relative humidity of 40%,
- in the adsorption unit 90% of moisture content in the air is removed,
- at the exit of each unit air and solid material have the same temperature
- the enthalpy reference is 0°C

Values used for calculations are given in Table A2-1, Appendix 3.2.

a. Adsorption Unit (see Figure A2-1)

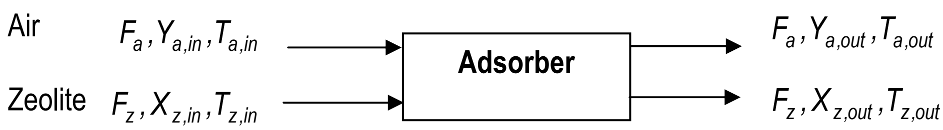

Figure A2-1: Adsorber input-output streams

Assumptions

- Balances are based on dry air and dry zeolite flows
- Dry air flow in equals dry air flow out: $F_{a,in} = F_{a,out} = F_a$
- Dry zeolite flow in equals dry zeolite flow out : $F_{z,in} = F_{z,out} = F_z$

The water mass balance is:

$$F_a Y_{a,in} + F_z X_{z,in} = F_a Y_{a,out} + F_z X_{z,out} \quad \text{(A2-1)}$$

The enthalpy balance for the adsorber is:

$$H_{a,in} + H_{z,in} = H_{a,out} + H_{z,out} + H_{ads} \tag{A2-2}$$

$$H_{a,in} = F_a((c_{p,a} + Y_{a,in}c_{p,v})T_{a,in} + \Delta H_v Y_{a,in}) \tag{A2-3}$$

$$H_{z,in} = F_z(c_{p,z} + X_{z,in}c_{p,w})T_{z,in} \tag{A2-4}$$

$$H_{a,out} = F_a((c_{p,a} + Y_{a,out}c_{p,v})T_{a,out} + \Delta H_v Y_{a,out}) \tag{A2-5}$$

$$H_{z,out} = F_z(c_{p,z} + X_{z,out}c_{p,w})T_{z,out} \tag{A2-6}$$

$$H_{ads} = \Delta H_{ads}(X_{z,out} - X_{z,in})F_z \tag{A2-7}$$

b. Regenerator Unit

The mass and enthalpy balances for regenerator are almost equal to that of the adsorber. However, here energy is required to release water from the zeolite.

$$H_{a,in} + H_{z,in} - H_{des} = H_{a,out} + H_{z,out} \tag{A2-8}$$

$$H_{des} = -H_{ads} \tag{A2-9}$$

Those balances are used to calculate the temperature and air humidity of the outlet streams. Analog equations as given for the adsorber are used.

c. Heater and Pre-Heater (see Figure A2-2)

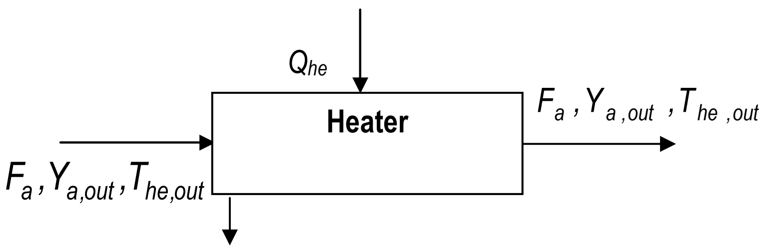

Figure A2-2: Heater input-output streams

The enthalpy balance for the heater is given as balance form:

$$H_{a,in} + Q_{he} = H_{a,out} \tag{A2-10}$$

The inlet and outlet air enthalpy follow from the stream conditions. The required heat for the heater is calculated.

d. Dryer (see Figure A2-3)

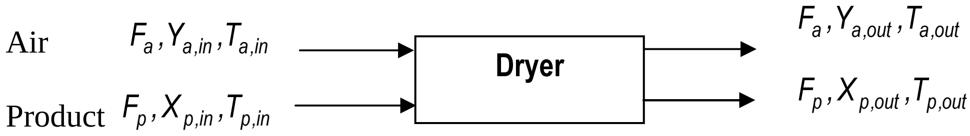

Figure A2-3: Dryer input-output streams

Assumptions

- Balances are based on dry air and product flows
- Dry air flow in equals dry air flow out: $F_{a,in} = F_{a,out} = F_a$
- Dry product flow in equals dry product flow out : $F_{p,in} = F_{p,out} = F_p$

In the dryer mass and energy exchange take place. The water balance using dry basis air and product flow are as follows:

$$F_a Y_{a,in} + F_p X_{p,in} = F_a Y_{a,out} + F_{p,out} X_{p,out} \tag{A2-11}$$

$$Y_{a,out} = RH_{out} Y_{sat}(T_{d,out}) \tag{A2-12}$$

where Y_{sat} represents the water vapor saturation line in the psychometric chart and depends on outlet dryer temperature ($T_{d,out}$), which follows from the enthalpy balance of dryer. The balances are:

$$H_{a,in} + H_{p,in} = H_{a,out} + H_{p,out} + H_{evap} \tag{A2-13}$$

$$H_{p,out} = F_p(c_{p,p} + X_{p,out} c_{p,w})T_{p,out} \tag{A2-14}$$

$$H_{evap} = \Delta H_v (X_{p,in} - X_{p,out})F_p \tag{A2-15}$$

$$H_{p,in} = F_p(c_{p,p} + X_{p,in} c_{p,w})T_{p,in} \tag{A2-16}$$

Physical constants and operational conditions are given Appendix 3.2. The product moisture content leaving the dryer ($X_{p,out}$) is set to 0.111 kg water/kg dry product, and outlet temperature of product and air equals ($T_{p,out} = T_{a,out} = T_{d,out}$). The flow of dry product and outlet dryer temperature are result of the calculations. The effect of product/air temperature on product moisture at given relative humidity proved to be minimal and is neglected.

e. Total of dried product

In the cross and counter multi stage dryer the amount of product can be dried is estimated based on the input of product flow.

$$F_{p,t} = F_a \frac{\sum_{d=1}^{d=n}(Y_{a,out,d} - Y_{a,in,d})}{X_{p,in,1} - X_{p,out,n}} \tag{A2-17}$$

$$F_{wp,t} = F_{p,t}(1 + X_{p,in,1}) \tag{A2-18}$$

$$F_{wa} = F_a(1 + Y_{a,in,1}) \tag{A2-19}$$

f. Cooler (see Figure A2-4)

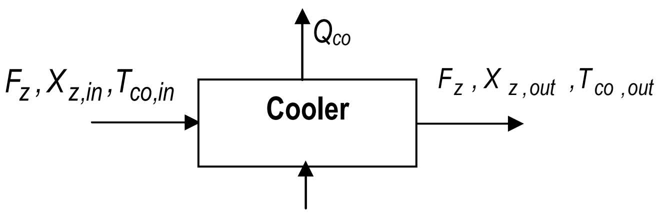

Figure A2-4: Cooler input-output streams

The enthalpy balance for the cooler is as follows:

$$H_{z,in} = Q_{co} + H_{z,out} \tag{A2-20}$$

The inlet and outlet air enthalpy follow from the stream conditions. The required cooling capacity is calculated.

Table A2-1: List of parameter values and physical properties applied for the calculations[1]

Parameter and Physical Properties	Value
The flow of wet ambient air for adsorber, kg/hr	1000
Humidity of ambient air, kg water /kg dry air	0.01
Temperature of ambient air, ^oC	25
The flow of dry air for dryer, kg/hr	991
Temperature of air entering first dryer, ^oC	70
Humidity of air entering first dryer, kg water /kg dry air	0.001
Flow of wet air entering first regenerator, kg/hr	250
Humidity of air entering first regenerator, kg water/kg dry air	0.01
The flow of dry air for regenerator, kg/hr	247
Temperature of air entering regenerator, ^oC	300
Water content in zeolite entering adsorber, kg water/kg dry zeolite	0.000
Temperature of zeolite entering adsorber, ^oC	35
Water content in zeolite exiting adsorber, kg water/kg dry zeolite	0.200
Temperature of fresh wet product, ^oC	25
Water content of fresh wet product, kg water/kg dry matter	2.333
Water content of product exiting system, kg water/kg dry matter	0.110
Relative humidity of air exiting each dryer, %	40
Operational pressure (bar)	1
Specific heat of dry air, kJ/kg ^oC	1
Specific heat of water vapor, kJ/kg ^oC	1.93
Specific heat of zeolite, kJ/kg ^oC	0.836
Specific heat of water, kJ/kg ^oC	4.180
Specific heat of dry product, kJ/kg ^oC	2.20
Heat of water adsorption, kJ/kg	3200
Heat of water evaporation, kJ/kg	2500

Appendix 3.3

Table A3-1: Stream Condition of Three Stage Counter Current Zeolite Dryer

Air Dryer Stream	Temperature °C	Moisture kg H_2O/kgdry air	Mass Flow kg/hr	Enthalpy Flow kJ/hr
Ambient to Adsorber, 1	25.00	0.0100	1000	49983
Adsorber,1 to Pre,Heater	51.62	0.0010	991	53679
Pre,heater to Dryer,1	70.00	0.0010	991	71916
Dryer,1 to Adsorber,2	40.00	0.0133	1003	73550
Adsorber,2 to Dryer,2	73.54	0.0013	991	76294
Dryer,2 to Adsorber,3	35.00	0.0170	1007	77830
Adsorber,3 to Dryer,3	77.18	0.0017	992	80873
Outlet Adsorber,3	38.73	0.0206	1011	90875
Product Stream	**Temperature °C**	**Moisture kg H_2O/kg dry product**	**Mass Flow kg/hr**	**Enthalpy Flow kJ/hr**
Outlet Dryer,1	40.00	0.1111	23	2225
Dryer,2 to Dryer,1	35.00	0.6945	35	2852
Dryer,3 to Dryer,2	30.00	1.4368	51	4388
Inlet Dryer,3	25.00	2.3333	70	5613
Zeolite Stream	**Temperature °C**	**Moisture kg H_2O/kg dry zeolite**	**Mass Flow kg/hr**	**Enthalpy Flow kJ/hr**
Cooler,1 to Adsorber,1	35.00	0.0000	45	1304
Adsorber,1 to Regenerator,1	51.62	0.2000	53	3845
Regenerator,1 to Cooler,1	166.33	0.0000	45	6195
Cooler,2 to Adsorber,2	35.00	0.0000	59	1734
Adsorber,2 to Regenerator,2	73.54	0.2000	71	7288
Regenerator,2 to Cooler,2	146.83	0.0000	59	7275
Cooler,3 to Adsorber,3	35.00	0.0000	76	2214
Adsorber,3 to Regenerator,3	77.18	0.2000	91	9766
Regenerator,3 to Cooler,3	127.45	0.0000	76	8063
Air Regenerator Stream	**Temperature °C**	**Moisuter Kg H_2O/kg dry air**	**Mass Flow kg/hr**	**Enthalpy Flow kJ/hr**
Ambient to Heater, 1	25.00	0.0100	250	12496
Heater,1 to Regenerator,1	300.00	0.0100	250	81879
Regenerator,1 to Heater,2	166.33	0.0460	259	73291
Heater,2 to Regenerator,2	300.00	0.0460	259	109315
Regenerator,2 to Heater,3	146.83	0.0939	271	101030
Heater,3 to Regenerator,3	300.00	0.0939	271	145815
Outlet Regenerator,3 (Exhaust Air)	127.45	0.1550	286	136924

Chapter 4

Energy Efficiency of Multistage Adsorption Drying for Low Temperature Drying

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Abstract

This work discusses the evaluation of multistage adsorption dryers with air dehumidification by zeolite and alumina pillared clay. In a multistage dryer product is dried in succeeding stages while air leaving a stage is fed to the next stage after dehumidification by an adsorbent. Energy efficiency of the drying system is evaluated for low temperature drying (10-50°C) and compared with conventional condenser drying. Results showed that the efficiency of the multistage adsorption dryers increase with the number of stages. For low drying temperatures zeolite is most favourable; for drying temperatures 40-50°C alumina pillared clay needs less cooling and deserves preference.

Keywords: multistage drying, adsorption, zeolite, alumina pillared clay, energy efficiency, condensation drying

List of Symbols

c_p	specific heat	(kJ/kg°C)
F	mass flow	(kg/hr)
H	enthalpy flow	(kJ/hr)
ΔH_v	evaporation heat of water	(kJ/kg)
M	condensation rate of water	(kg/hr)
Q	heat flow	(kJ/hr)
T	temperature	(°C)
X	water content in solid material	(kg water/kg dry material)
ΔT_{min}	minimum temperature for heat transfer	(°C)
η_{energy}	energy efficiency	(%)

Subscripts

c	cold stream	*cool*	cooling	*evap*	evaporation
h	hot stream	*he*	heater	*in*	inlet
min	minimum	*out*	outlet	*p*	dry product
rec	recovery	*req*	required		
trns	transfer	*w*	water		
i,j,k	stream number	*n, m,l*	total number		

1. Background

Low temperature drying in the temperature range 10-50°C is favorable to limit product deterioration such as browning, shrinkage and structure deformation, the loss of valuable organic content is inhibited and product quality is retained [1] . However, the processes are expensive, need long operational time, and are complex if applied under vacuum and/or refrigerating conditions. Moreover, energy efficiency is below that for high temperature drying.

In conventional low temperature dryers water is removed from the air by condensation. The air is cooled air below the dew point temperature and subsequently heated up to the drying temperature. The dehumidified air is then used for drying, but the total energy efficiency is mostly below 50%. Therefore, it is a challenge to improve the energy efficiency and also to speed up the drying rate for low temperature drying. For example, Sosle et al [2] applied a heat pump for air dehumidification to enhance the performance. However, compared to the conventional dryer, the result did not affect energy efficiency and drying time significantly. Xu et al [3] proposed a combination of a vacuum freeze dryer and a convective air dryer in two successive stages. This system could be a potential option, since the product quality is maintained. The result with a energy efficiency of 50-60% is only meaningful as an alternative for vacuum freeze dryers.

Air dehumidification by adsorbents is another option to enhance the drying efficiency. [1,4,5,6] With this method, the air is dehumidified by adsorbing water while the air temperature increases at the same time due to the release of the adsorption heat. As a result, the dryer inlet air can contain more sensible heat for drying which improves the total energy efficiency. Moreover, with a lower humidity, the driving force of drying is improved and as a result the drying time is reduced. Simulation studies of single and multistage zeolite drying for the temperature range 50-90°C showed that a energy efficiency of 75-90% can be achieved, and in special configurations for heat recovery the efficiency may go up to 120%. [6,7]

For low temperature drying in the range 10-50°C, the possibilities for heat recovery differ from medium temperature drying in multistage zeolite dryers. [8] Another aspect is that in medium temperature drying the dehumidified air needs additional heating, while for low temperature drying it can be necessary to cool the air after dehumidification. Both aspects result in a lower energy efficiency of multistage adsorption dryers.

This paper evaluates the energy efficiency of low temperature adsorption dryers using zeolite and alumina pillared clay for air dehumidification compared to condensation dryers by taking into account the energy for heating and cooling. The effects of the number of stages, dryer inlet temperature and ambient air on the energy efficiency of the dryers are discussed.

2.Methodology

The energy efficiency is evaluated for dryers operating with inlet temperatures in the range10-50°C, using Dutch ambient air conditions throughout the seasons (see Table 4.1). Air is dehumidified by zeolite, alumina pillared clay and by a condensation dryer. For the material properties, operation conditions, assumptions and steady state mass and energy balances is referred to previous work of Djaeni et al [6] and Yamanaka et al [9].

Table 4.1: Average ambient Dutch air conditions in different seasons

Temperature /Relative Humidity	10°C /80%	15°C /70%	20°C /60%	25°C /50%
Humidity kg vapor/kg dry air	0.006	0.007	0.009	0.01

2.1. Process Description

2.1.1. Conventional condensation dryer

Figure 4.1 presents the configuration of the condensation dryer. Ambient air is cooled below its dew point and water condenses in the condenser. The cooled air from the condenser is used either for cooling the air in the chiller (if the ambient air temperature is above the exhaust air from dryer) or for cooling the recycle air from the dryer (if the ambient air temperature is below the exhaust air from dryer). The dried air is then heated in the heater to the dryer inlet temperature conditions.

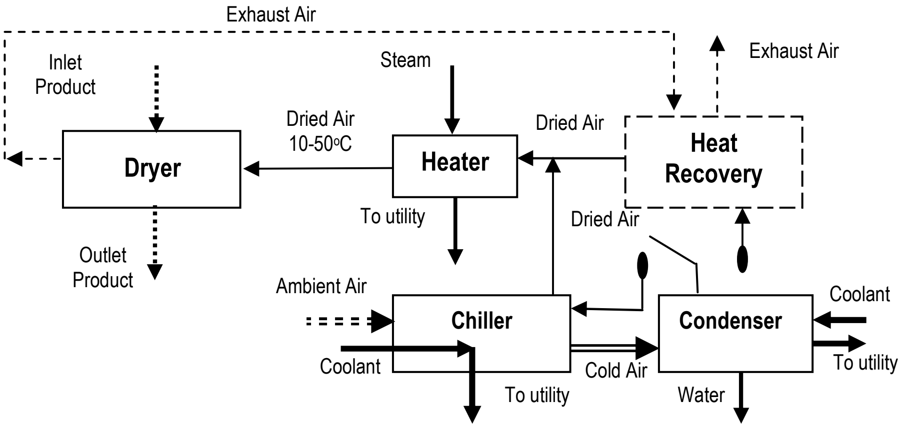

Figure 4.1: Low temperature condensation dryer

2.1.2. Multistage adsorption dryer

The counter current multistage dryer is given in Figure 4.2.[7] Ambient air is dehumidified in the first adsorber till 90% and 70% below the input value by using zeolite and alumina pillared clay respectively. In the adsorber the air temperature increases due to the release of the adsorption heat. Depending on the drying conditions, the dried air is cooled or heated in the conditioner before the air is fed to the dryer. Meanwhile, saturated adsorbent is sent to the regenerator to release water in the temperature range 120-300°C. The desorption heat is 3200 kJ/kg water for zeolite and 2600 kJ/kg water for alumina pillared clay. [6,9] For the next stage, air leaving the dryer and regenerator is re-processed for use in the next stage. The product comes from the adjacent dryer up stream and is dried further in the current stage.

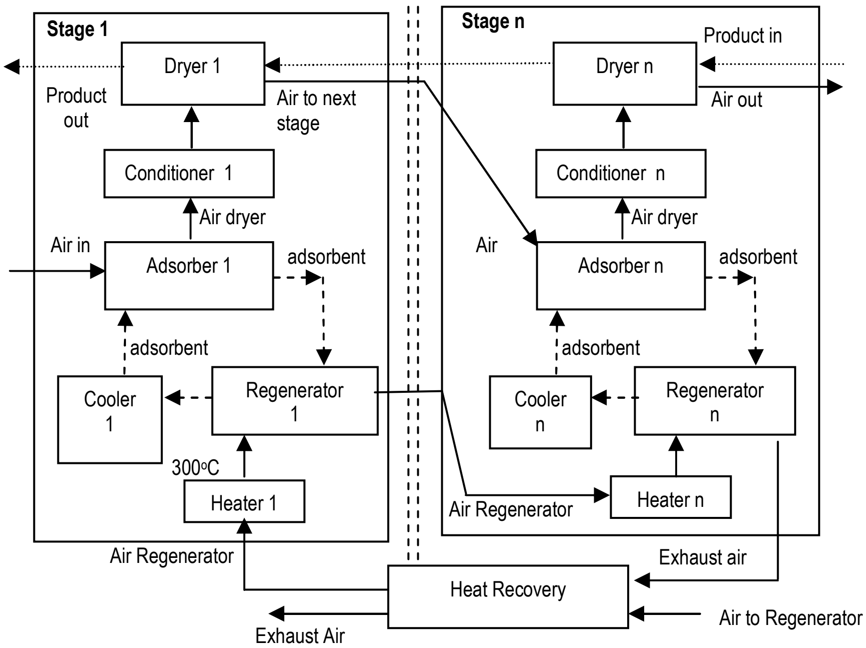

Figure 4.2: Multistage counter-current low temperature adsorbent dryer

2.2. Heat Recovery

The heat recovery unit used for both the condensation and adsorption dryers [6,10] is based on the pinch concept from Linnhoff.[11] The heat transfer calculations are based on a minimum temperature difference of 10°C. The analysis showed that in the conventional condenser dryer systems (see Figure 4.1) the exhaust air from the dryer can be used to heat the cooled air from condenser. For the adsorption dryers (see Figure 4.2), the exhaust air from the regenerator and the adsorbent leaving the regenerator can be reused for heating the air which is sent to the regenerator before heater 1.

Table 4.2 presents the temperatures of the hot and cold streams in the adsorption dryer system. The dehumidified air from the adsorber is adjusted to the operational drying temperature in the range 10-50°C. The function of the conditioner (cooling or heating) depends on the ambient condition. For ambient air at 25°C, humidity 0.01 kg water/kg dry air, and flow rate of 1000 kg/hr, the dehumidified air from the adsorber is about 52°C by using zeolite and 41°C by alumina pillared clay. For lower ambient air temperatures, the air temperature from the adsorber will be lower (see Table 4.3). In this case, the conditioner needs to heat the dehumidified air when the aimed dryer inlet is above the temperature of air from the adsorber. For lower dryer inlet temperatures the conditioner needs to cool the air.

Table 4.2 shows that the cold streams 2,3,..,n cannot be heated up by the hot streams, since they are at same level. For heat recovery only the zeolite flow and the exhaust air flow from the regenerators (hot 1 and 2) can be combined with the air fed to the regenerator 1 (cold 1). Air from the adsorber can be used as cold 2 when the temperature is below the dryer inlet temperature, or it can be used as a hot stream (hot 3 in Figure 4.3) when its temperature is above the dryer inlet temperature. Figure 4.3 presents the possible configuration for heat recovery.

Table 4.2: Overview of hot and cold streams

Type	Stream	T (source) °C	T (target) °C	Enthalpy flow kJ/hr
Hot Stream				
Hot 1	Zeolite from regenerator 1,2,.,n	120-160	35	6000-13200*
Hot 2	Exhaust air from regenerator-n	120-160	35	75000-125000*
Cold Stream				
Cold 1	Air entering regenerator- 1	25	300	12500
Cold 2	Air entering regenerator- 2	120-160	200	73300*
Cold n	Air entering regenerator -n	120-160	200	75000*

* the values for enthalpy flow depend on the stage number

Table 4.3: Temperature of air exiting first adsober in different air ambient

Ambient temperature (°C)	Humidity kg water/kg dry air	Ambient Relative Humidity %	Temperature of air from the first adsorber (°C) zeolite/pillared clay
10	0.006	80	27/22
15	0.007	70	34/28
20	0.009	60	44/36
25	0.01	50	52/41

The heat recovery system is presented in Figure 4.3. The amount of heat recovery is calculated by summarizing the heat transferred in each heat exchanger and concerns sensible and latent heat.

For $Fc_{p,c} \geq Fc_{p,h}$, the total heat recovered is

$$Q_{trns,total} = \sum_{i=1}^{n}\sum_{j=1}^{m} F_{h,i}^{j} c_{p,h,i}^{j} (T_{h,i}^{j} - (T_{c,i}^{j} + \Delta T_{min})) + M_{w,i}^{j} \Delta H_{v} \tag{1}$$

If $Fc_{p,c} \leq Fc_{p,h}$, the total heat recovery is:

$$Q_{trns,total} = \sum_{i=1}^{n}\sum_{j=1}^{m} F_{c,i}^{j} c_{p,c,i}^{j} (T_{h,i}^{j} - (T_{c,i}^{j} + \Delta T_{min})) \tag{2}$$

$$Q_{rec} = Q_{trns,total} \tag{3}$$

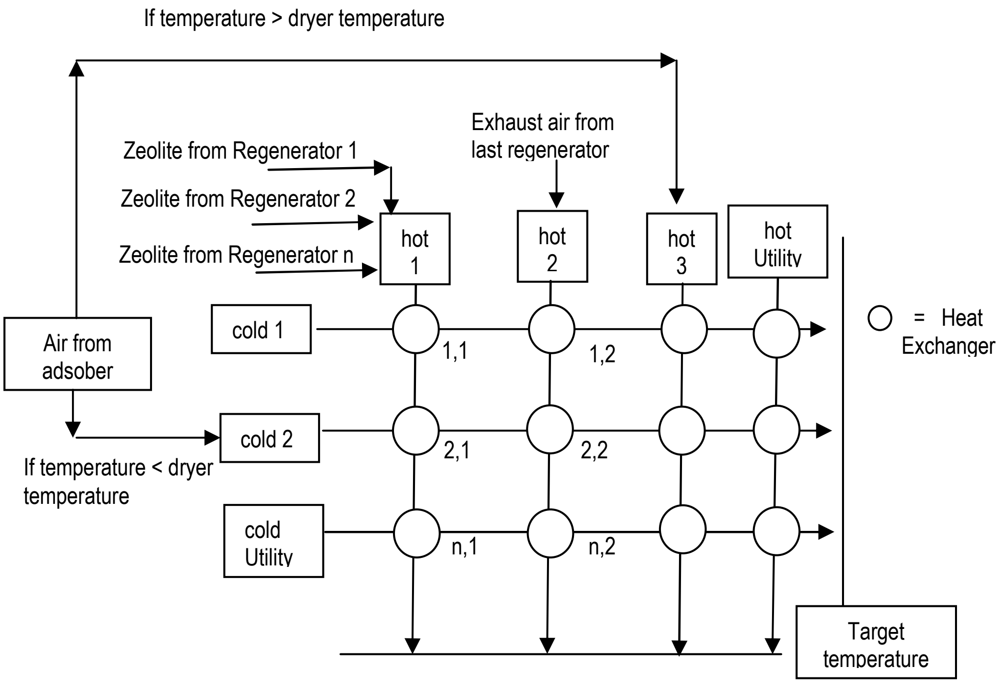

Figure 4.3: Heat recovery unit for improving the total energy efficiency

2.3. Performance evaluation

The performance evaluation uses the overall energy efficiency as main indicator. The energy efficiency is estimated by taking into account energy for heating and cooling. Energy for heating is derived from heat required to the system after recovery. While, the energy for cooling is based on the energy to cool the dehumidified air to reach dryer condition. The energy efficiency can be as follows:

$$\eta_{energy} = \frac{Q_{evap}}{Q_{cool} + Q_{req}} 100\% \tag{4}$$

with Q_{evap} as the total heat required for evaporating water from the product, and is defined by:

$$Q_{evap} = F_p c_{p,h} (X_{p,in} - X_{p,out}) \Delta H_v \tag{5}$$

Q_{req} is the total of net heat used by the dryer system an follows from the total heat introduced in all heaters minus the total recovered heat:

$$Q_{req} = \sum_{i=0}^{i=n} (Q_{he})_i - Q_{rec} \tag{6}$$

At the conventional condenser dryer, the air is cooled to bring the air temperature below its dew point and to condense the moisture in the air (see Figure 4.1). Whereas, for adsorption dryer, cooling can be required after the adsorber to bring the air temperature at the dryer condition (see Figure 4.2). In general, the energy for cooling can be expressed as follows:

$$Q_{cool} = \sum_{i=1}^{n} F_h c_{p,h} (T_{h,in} - T_{h,target}) + M_{w,i} \Delta H_v \quad (7)$$

with Q_{cool} as the energy for cooling in each condenser, cooler and conditioner, kJ/hr (for adsorption dryer, $M_{w,i} \Delta H_v = 0$)

3. Results and discussion

3.1. Effect of temperature and number of stages on efficiency

Figure 4.4 presents the energy efficiency of a single-stage (number of stages is 1) and a series of multistage zeolite dryers which operate at different dryer inlet temperatures and use ambient air at 25^{o}C and with absolute air humidity of 0.01 kg water/kg dry air (i.e. 50% relative humidity).

The energy efficiency of the adsorption dryer increases with increasing operational temperature and stage number. For dryer inlet temperatures at 30°C and below, the number of stages has a significant effect on the energy efficiency which indicate that heat recovery of the exhaust air leaving the regenerators (hot 2) is significant. For 40°C, above three stages the improvement is marginal and in such application a three stage dryer seems economically most promising.

In these systems only hot streams with high temperatures are used for heat recovery. The heat in the air leaving the adsorbers is not recovered since all cold streams need higher temperature levels (see Table 4.1 and 2). Thus the adsorption heat obtained in the adsorbers is not used.

Figure 4.4 shows also that the energy efficiency goes down for the lower operational temperatures. This outcome is result of the lower capacity of the dehumidified air for taking up water from the product at low temperatures. Moreover, for low temperature drying (<30^{o}C) the conditioner requires more energy for cooling which cannot be recovered (see Table A.1, Appendix 4).

Compared with zeolite, alumina pillared clay has a lower capacity to adsorb water from air, and alumina pillared clay cannot be applied as adsorbent for temperatures below 20°C (see also Table A.1, Appendix 4). The lower capacity for adsorption of alumina pillared clay at low temperatures results in a lower degree of dehumidification and thus a lower driving force for drying. Hence, the energy efficiency of alumina pillared clay for low temperatures is below that of the dryer using zeolite; while at 30°C the performance is equal. At 40°C, the energy efficiency of alumina pillared clay system is higher than that of zeolite, since the zeolite system needs more energy to cool the released adsorption heat. As a consequence, by choosing an adsorbent with a lower adsorption heat, the energy for cooling can be minimized; even up to zero (see Table A.1, Appendix 4).

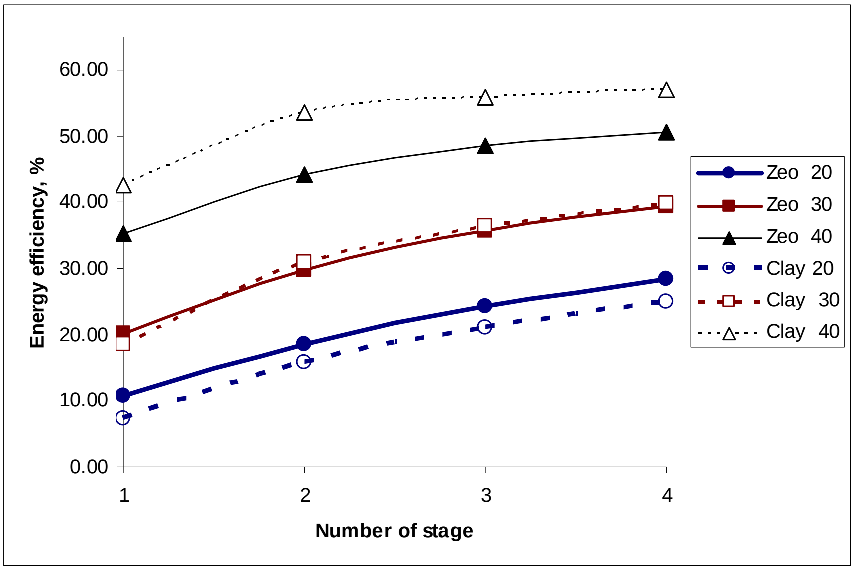

Figure 4.4: Energy efficiency for the multistage dryers as a function of the number of stages and drying temperature. $T_{ambient}$=25°C, $Y_{ambient}$=0.010 kg water/kg dry air, and F_{air}= 1000 kg/hr. Zeo refers to zeolite, and Clay refers to alumina pillared clay

3.2 Varying ambient conditions

The performance of the adsorber dryers is evaluated for different ambient temperatures and compared to dryers with dehumidification by condensation. The considered multistage adsorption dryer is a three stage counter current system.

Figure 4.5 presents the energy efficiency of the condensation dryer and the three stage adsorbent dryers using zeolite and alumina pillared clay respectively. The results show that for the lower ambient temperatures, the energy efficiency of the adsorbent dryers surmounts that of the condensation dryer. This outcome is sum of the following aspects:

1. at one hand, for low ambient temperatures, more energy is required to bring the air temperature from the low values to the drying temperature, and
2. also at lower ambient temperatures a lower amount of water is removed from the air, thus less heat is released in the adsorber which has to be compensated by additional heating,
3. but, the required extra heat is gained from the heat recovery units which makes the system more efficient, especially for ambient air temperature below 20°C, and

4. because of the lower amount of water adsorbed in the adsorbers, less water has to be removed from the adsorbent in the regenerator; therefore the regenerator requires less energy, and

5. finally, the energy for cooling decreases, since the temperature of the dehumidified air is close to the dryer inlet temperature.

All these aspects make the total balance profitable for the adsorbent systems.

For dryer inlet temperatures above 40°C, the energy efficiency of the conventional condensation dryers increase for decreasing ambient temperature. The ambient air is not very suitable as hot stream. Thus, the exhaust air from the dryer can be used as hot stream in which increases the heat recovery. In addition, decreasing ambient air temperature also causes the energy for cooling being lower due to less water content to be condensed in ambient air (see Table A.2, Appendix 4).

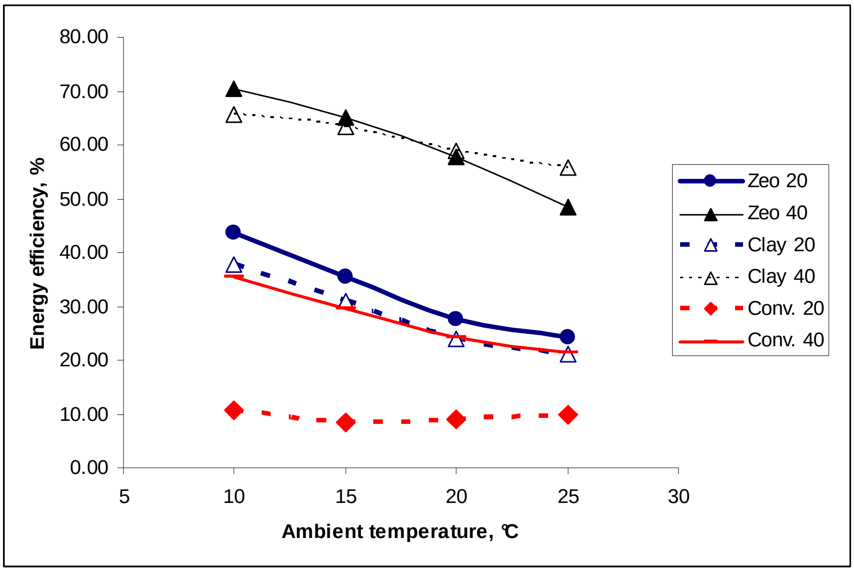

Figure 4.5: The effect of ambient temperature and dryer inlet temperature on the energy efficiency. Zeo: zeolite dryer, Conv: conventional condenser dryer, Clay: alumina pillared clay

4. Conclusion

The energy efficiency of multistage adsorption dryers is significantly better than that of conventional condenser dryers. The ambient air used for drying and the temperature of air fed to the dryer are important parameters for the energy efficiency.

For drying inlet temperatures below 30°C the zeolite dryer is beneficial since the air fed to the dryer has a low water content resulting in a high driving force for drying. For 40-50°C, the multistage dryer with alumina pillared clay needs no cooling while the zeolite system has to be cooled for these conditions. As a result, for these drying temperatures the alumina pillared clay is advantageous compared to zeolite.

Acknowledgement

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Appendix 4

Table A.1: Energy for heating and cooling, and energy efficiency of adsorption dryer using zeolite and alumina pillared clay dryer for stage 1 to 4

Inlet Ambient	Dryer Condition, °C									
25°C 50% RH	10	20	30	40	50	10	20	30	40	50
Zeolite Dryer	**Energy for heating (Q_{req}), kJ/hr**					**Energy for cooling (Q_{cool}), kJ/hr**				
Stage 1	36267	36286	36282	36285	36284	41283	31363	21443	11523	1603
Stage 2	44472	48483	54318	60565	67430	44915	35409	25822	16071	6087
Stage 3	51705	59944	71812	84819	99310	46709	37981	29171	20087	10565
Stage 4	59372	72513	90240	110023	132034	48467	40512	32484	24077	15033
	Heat for water evaporation (Q_{evap}), kJ/hr					***Energy efficiency, %**				
Stage 1	3750	7250	11650	16800	22500	4.84	10.72	20.18	35.14	59.39
Stage 2	8850	15500	23900	33850	45050	9.90	18.48	29.82	44.17	61.28
Stage 3	13950	23750	36150	50900	67600	14.17	24.25	35.80	48.52	61.52
Stage 4	19100	32000	48450	67950	90100	17.71	28.31	39.48	50.67	61.26
Alumina Pillared Clay	**Energy for heating (Q_{req}), kJ/hr**					**Energy for cooling (Q_{cool}), kJ/hr**				
Stage 1		37900	37900	32973	32969		21256	11298	1339	0
Stage 2		44008	48993	53556	60202		26033	14199	1712	0
Stage 3		57951	67582	78110	86708	-	27590	15223	1715	0
Stage 4		70899	86015	102898	121681		28749	15966	1716	0
	Heat for water evaporation (Q_{evap}), kJ/hr					***Energy efficiency, %**				
Stage 1		4360	9148	14616	20650		7.37	18.59	42.60	62.63
Stage 2		11017	19526	29579	40926		15.73	30.90	53.52	67.98
Stage 3		17957	30092	44602	61136		20.99	36.34	55.87	70.51
Stage 4		24933	40684	59635	81335		25.02	39.89	57.00	66.84

* Energy efficiency based on $\eta_{energy} = \frac{Q_{evap}}{Q_{cool} + Q_{req}} 100\%$

Table A.2: Cold and hot utility, heat evaporation, and energy efficiency of adsorption and conventional dryer at various ambient condition

Ambient Condition		Dryer Condition, °C									
°C	**% RH**	**10**	**20**	**30**	**40**	**50**	**10**	**20**	**30**	**40**	**50**
Zeolite Dryer		**Energy for heating (Q_{req}), kJ/hr**					**Energy for cooling (Q_{cool}), kJ/hr**				
10	**80**	35431	43789	54183	65632	80410	21265	12499	6707	7553	7967
15	**70**	39973	48291	57956	71231	89996	28951	20194	11363	7806	8217
20	**60**	47467	55854	67725	80091	94478	39295	30558	21741	8311	8714
25	**50**	51705	59944	71812	84819	99310	46709	37981	29171	20087	10565
		Heat for water evaporation (Q_{evap}), kJ/hr					***Energy efficiency, %**				
10	**80**	14750	24500	36850	51600	68300	26.02	43.53	60.52	70.51	77.28
15	**70**	14550	24300	36350	51400	68100	21.11	35.48	52.44	65.03	69.34
20	**60**	14150	23950	36700	51050	67750	16.31	27.72	41.02	57.75	65.65
25	**50**	13950	23750	36150	50900	67600	14.17	24.25	35.80	48.52	61.52
Alumina Pillared Clay		**Energy for heating (Q_{req}), kJ/hr**					**Energy for cooling (Q_{cool}), kJ/hr**				
10	**80**		47979	62247	70562	80051	-	5254	1283	0	0
15	**70**		50664	60310	72406	82683	-	12184	1950	0	0
20	**60**		56013	64446	76344	88587	-	21126	8788	0	0
25	**50**		57951	67582	78110	86708	-	27590	15223	1715	0
		Heat for water evaporation (Q_{evap}), kJ/hr					***Energy efficiency, %**				
10	**80**		20026	31980	46340	62757		37.62	50.34	65.67	78.40
15	**70**		19501	31502	45900	62347		31.03	50.60	63.39	75.40
20	**60**		18467	30557	45031	61537		23.94	41.73	58.98	69.46
25	**50**		17957	30092	44602	61136		20.99	36.34	55.87	70.51
Condenser Dryer		**Energy for heating (Q_{req}), kJ/hr**					**Energy for cooling (Q_{cool}), kJ/hr**				
10	**80**		12888	17763	23335	29484		15026	15026	15026	15026
15	**70**		12875	17745	23312	29455		22545	22545	22545	22545
20	**60**		9987	17710	23266	29396		22537	32554	32554	32554
25	**50**		4989	14966	23243	29367		25116	25116	40082	40082
		Heat for water evaporation (Q_{evap}), kJ/hr					***Energy efficiency, %**				
10	**80**	-	2967	7952	13595	19775		10.63	24.25	35.44	44.43
15	**70**	-	2964	7945	13582	19755		8.37	19.72	29.62	37.99
20	**60**	-	2957	7929	13555	19716		9.09	15.77	24.28	31.83
25	**50**	-	2955	7920	13541	19697		9.82	19.76	21.38	28.36

* **Energy efficiency based on** $\eta_{energy} = \frac{Q_{evap}}{Q_{cool} + Q_{req}} 100\%$

Chapter 5

Computational Fluid Dynamics for Multistage Adsorption Dryer Design

Published in: Drying Technology **2008**, *26*(4),487-502

Abstract

Two-dimensional Computational Fluid Dynamics calculations for multistage zeolite drying are performed for two dryer configurations 1) a continuous moving bed zeolite dryer and 2) a discrete bed zeolite dryer. The calculations concern drying of tarragon (*Artemisia dracunculus L.*) as a herbal product. The results reveal the profiles of water, vapor and temperature in dryer, adsorber and regenerator in the flow directions. The energy efficiency ranges between 80-90% and is close to overall model calculations. The performance of continuous moving bed zeolite dryer is the best. Residence time of air, product and zeolite are in accordance to other drying systems.

Key words: adsorber, dryer; regeneration; zeolite; tarragon; energy efficiency; CFD-model; moving bed dryer

List of Symbols

A_{ads}	constant of adsorption	(1/hr)
A_{des}	constant of desorption	(1/hr)
A_{dry}	constant of drying	(1/hr)
$C_{0,1,2,..n}$	Oswin constant	
D	diffusivity coefficient	(m^2/hr)
E_{ads}	activation energy of adsorption	(kJ/kmol)
E_{des}	activation energy of desorption	(kJ/kmol)
F	flow of material	(kg/hr)
ΔH_{ads}	heat of water adsorption	(kJ/kg)
ΔH_v	latent heat of water evaporation	(kJ/kg)
Q	heat flow	(kJ/hr)
R	gas constant	(kJ/kmole K)
RH	relative humidity	(%)
T	temperature	(^{o}C)
U	overall heat transfer coefficient	(kJ/hr m^2 C)
c_p	specific heat	(kJ/kg°C)
h	height of equipment	(m)
k	conductivity of component	(kJ/m°C)
l	length of equipment	(m)
q	moisture content in dry material	(kg moisture/kg dry material)
r_{ads}	rate of adsorption	(kg/hr)
r_{des}	rate of desorption	(kg/hr)
r_{dry}	rate of drying	(kg/hr)
t	time	(hr)
x, y	coordinate	
w	width of equipment	(m)
ρ	density	(kg/m^3)
η	thermal efficiency	(%)

Subscripts

a	dry air	*ad*	adsorber	*ads*	adsorption
ar	air regenerator	*d*	dryer	*des*	desorption
dry	drying	*e*	equilibrium	*evap*	evaporation
in	inlet	*out*	outlet	*p*	dry product
r	regenerator	*rec*	recovery	*req*	required
s	solid	*v*	vapour	*w*	water
z	dry zeolite				

1. Background

Convective drying is based on the evaporation of water from the products to be dried. The release of water from the material and the water phase change from liquid to vapour, requires a significant amount of heat which is difficult to recover. As a consequence drying efficiency, defined as the ratio between the amount of heat required to evaporate the water from the product and the amount of heat used, is for low temperature drying (20-50°C) in the range of 40-50% [1] and for medium temperature drying (50-90°C) in the range 50-60%. [2] Regarding the costs of energy and the need to reduce energy consumption new low energy consuming drying concepts have to be developed. Recent work has shown that adsorption drying with zeolites, silica and other adsorbents is promising to reduce energy usage and operational cost. [3] Based on experimental result of drying wheat conducted by Revilla et al, [4] it proved that zeolite has the highest water adsorption capacity and the fastest adsorption rate compare to other water adsorbents such as alumina pillared clay, sand and natural clay

Using a multistage drying system with zeolites has special advantages. Steady-state calculations performed in previous studies of Djaeni et al. [5] showed that the efficiency of a 2-4 stage adsorption dryer using zeolite in combination with heat recovery is in the range 80-90%. If the latent heat of the exhaust air is recovered by compression of the exhaust air the energy efficiency goes even up to 120%.[5] However, it must be noted that the applied steady-state calculations using an overall model are quite straightforward. Product properties are not taken into account, the water gradient and the distribution of temperatures in the equipment are not specified, the effects of these distributions on adsorption an drying rate were neglected, etcetera. Hence, no information on the dimensions of the equipment is given in that work.

For a detailed study on the phenomena in multistage drying systems Computational Fluid Dynamics (CFD), using spatial models of the dryer, adsorption and regeneration system, is a powerful tool. Wanjari et al. [6] present a spatial model for fluid bed dryers and use it as a tool for design. Some examples are given for spatial modeling of water adsorption and desorption in zeolite systems.[7-11] In these publications it was shown that dynamic simulation of adsorption and desorption using 2-dimensional models and CFD calculations, gives a lot additional information on the process characteristics; for example how the system reacts on different flows, temperatures and water contents in the system.

The examples in the literature consider adsorption and desorption systems only; thus not in combination with a drying process. In this work combined adsorber, regenerator and dryer and their interactions will be considered. CFD calculations reveal the distribution of temperature and moisture distribution in these systems and give information about the required dimensions and layout of the system. Moreover, because the temperature and moisture distribution in the system are taken into account the calculations are more accurate.

2. System description

In multistage zeolite dryers fresh air fed to the dryer is dehumidified by zeolite before drying. After passing a first drying stage, the air is several times reused for drying after another pass through a bed with zeolite. The lay-outs of the multistage zeolite dryer systems which are considered in this work are given in Figures 5.1 and 5.2.

In the multistage dryer system with a continuous moving bed of zeolite (CMBZ-dryer) as presented in Figure 5.1, the zeolite moves in a series of succeeding adsorbers which are directly connected to each other; i.e. zeolite that leaves an adsorber stage is directly fed to the next stage. After the last stage the zeolite is fed to the regenerator. This system can be used in co-current or in counter-current flow for the zeolite and the product.

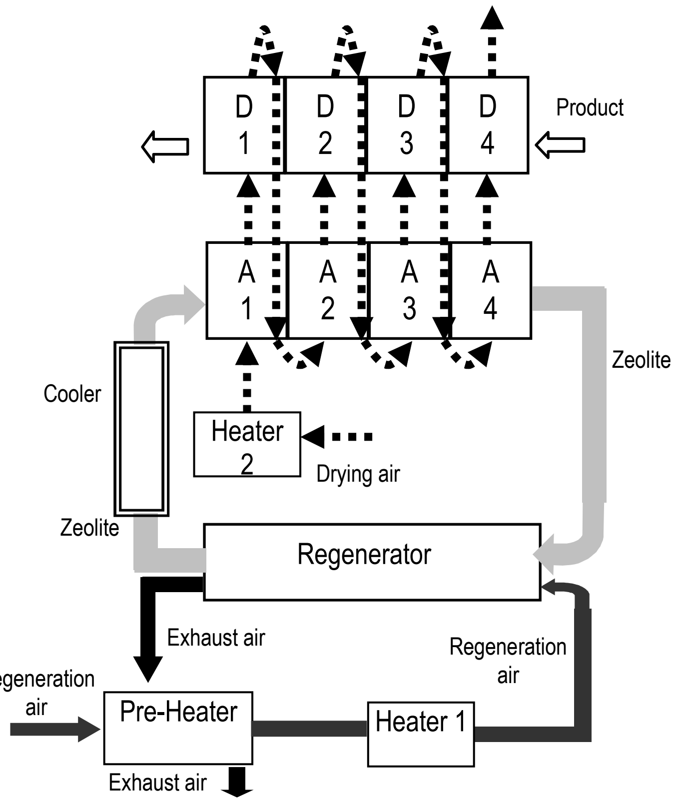


Figure 5.1: Modified Multistage dryer with a Continuous Moving Bed of Zeolite (CMBZ-dryer); A=Adsorber, D=Dryer

Figure 5.2 represents the multistage dryer with a discrete bed of zeolite (DBZ-dryer). In this system, the zeolite from regenerator is distributed in each adsorber. Hence, for each adsorber stage, the wet air contacts with dried zeolite (see also Figures 5.1 and 5.2 for comparison). After adsorbing water vapor, the spent zeolite from each adsorber is then collected and sent to regenerator (see zeolite stream at Figure 5.2). This system is similar to that of the previous work of Djaeni et al.[5]

For both cases the regenerated zeolite is cooled down to 35°C and then fed to the adsorbers. Hereby the airflow towards the adsorber is used for cooling. Furthermore the regenerator exhaust air is used to preheat the air which is fed to regenerator.

For both cases, the adsorber and dryer are split in four stages and counter and co current flows of adsorbents and product are considered. The regenerator is one system and not split as the adsorber and dryer. In this work only the efficiency of adsorber, regenerator and dryer are considered and compared with the previous work of Djaeni et al. [5] Further efficiency improvement by exhaust air compression could be an independent extension to this system.

The systems given in Figure 5.1 and 5.2 are applied to dry tarragon (*Artemisia dracunculus L.*) in a moving bed system. Tarragon is used as a herbal medicine or as a spice for cooking. Drying characteristics for tarragon as sorption isotherms, drying kinetics and physical properties taken from Arabhosseini et al. [12]

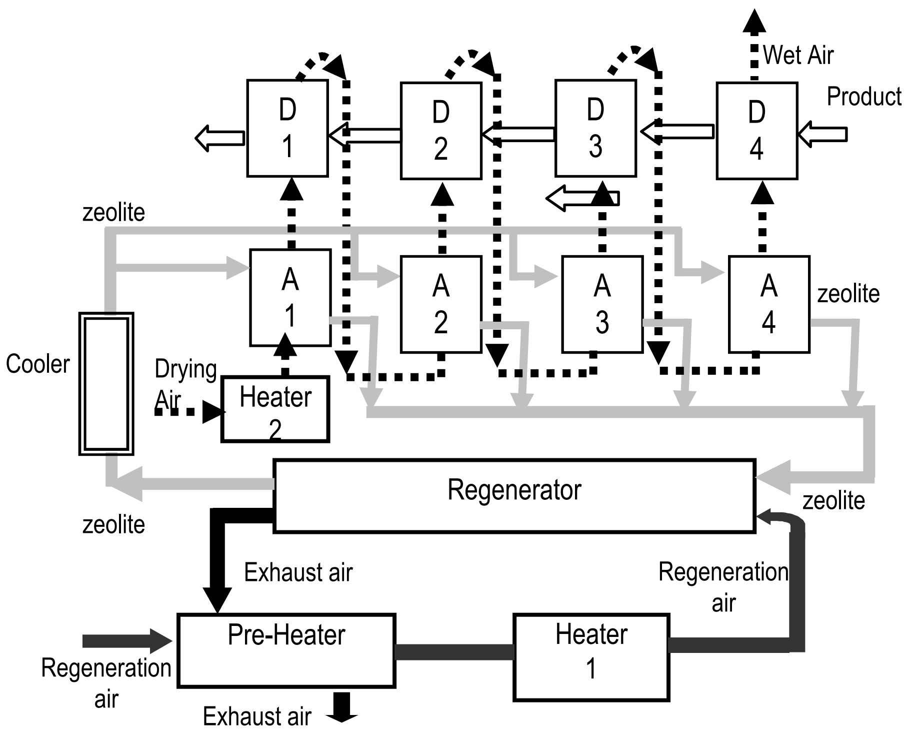


Figure 5.2: Multistage dryer with a Discrete Bed of Zeolite (DBZ-dryer); A=Adsorber, D= Dryer

3. Modeling

For the modeling step, the overall process diagrams from Figure 5.1 and 5.2 are transferred to detailed flow diagrams in which all flows and their properties are specified. Figure 5.3 concerns the detailed diagram for the counter current multistage zeolite dryer with continuous adsorber that is given in Figure 5.1. A similar diagram can be made for the discrete adsorber system.

3.1. Assumptions

The mathematical model is based on following assumptions:

1. The flow of air is turbulent-plug flow
2. The distribution of temperature and water content is 2-dimensional (*x* and *y* direction)
3. Pressure drop over the equipment is neglected
4. Processes are adiabatic; i.e. no heat exchange with the environment
5. Physical properties as density, specific heat, and diffusion coefficients is constant
6. Only the dynamics and spatial distribution in the adsorber, dryer and regenerator are considered; transport phenomena for cooler, heater, and pipes are instantaneous
7. Flow of dry air, zeolite, and product through the stages is constant
8. The equilibrium moisture of the zeolite is according to the modified Oswin relation (raw data cited from CECA, [13])
9. Tarragon with the properties given by Arabhoseini et al [12] used in this work

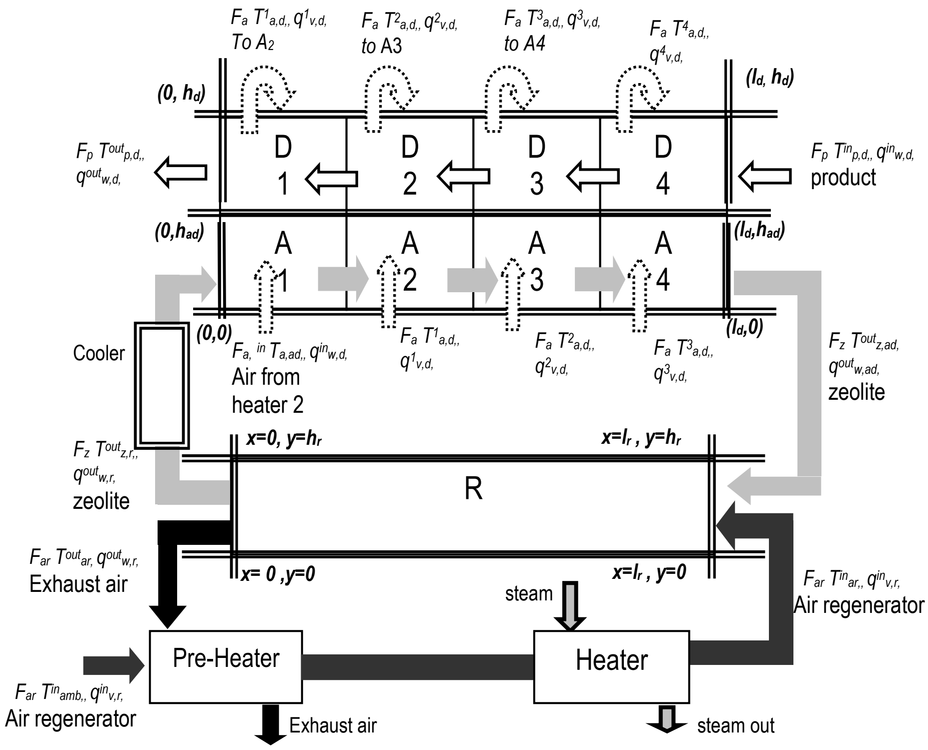


Figure 5.3: Detailed diagram of a four stage counter current zeolite dryer. A=adsorber, D=Dryer, R=regenerator, *F*= mass flow (kg/hr dry basis), *T*=Temperature (°C), *q*= water content. note: adsorber coordinates are defined as: $x=0$ to l_d, and $y=0$ to h_{ad}; dryer coordinates: $x=0$ to l_d, and $y=h_{ad}$ to h_d, regenerator coordinates: $x=0$ to l_r, and $y=0$ to h_r). Air from a drying stage is fed to the next adsorber stage.

3.2. Mass and energy balances

Mass and energy balances for product to be dried, the zeolite in the adsorber, and the zeolite in the regenerator have much common. The main differences are the kinetics for drying, adsorption and desorption, and the air flow direction in the equipment. Figure 5.4 illustrates a grid representation for a part of the adsorber and dryer where the zeolite moves at horizontal direction from left to the right side, and air moves from the bottom to the top of adsorber (vertical direction). The air flow is in cross current with the zeolite. In the regenerator zeolite and air and zeolite are in the same direction. For the balances water and energy exchange between air and solid material, conductive and convective transport have to be considered. Moreover, in the adsorber heat is released due to adsorption which results in an increasing temperature of the zeolite and air, whereas in the dryer and regenerator product/zeolite and air temperature decrease.

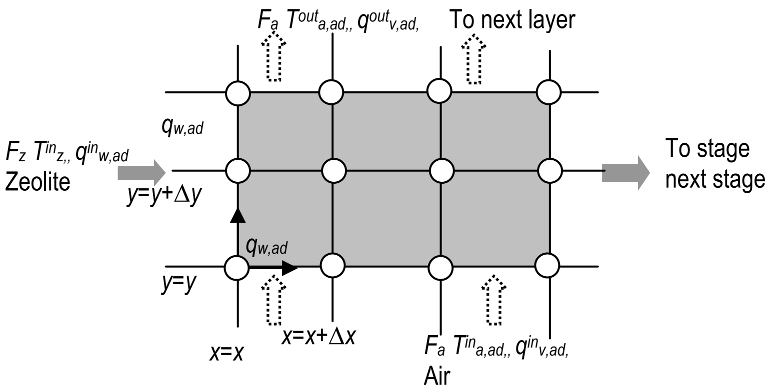


Figure 5.4: Grid representation for adsorber and dryer

The accumulation of water in adsorbent and product is a function of water transport due to diffusion, convection and water uptake/release:

$$\frac{dq_{w,s}}{dt} = D_w \nabla^2 q_{w,s} - F_s \nabla q_{w,s} \pm \textit{rate of water transfer} \tag{1}$$

For the accumulation of water in air a similar expression is applied but now the water uptake/release is in the opposite direction:

$$\frac{dq_{v,a}}{dt} = D_v \nabla^2 q_{v,a} - F_a \nabla q_{v,a} \mp \textit{rate of water transfer} \tag{2}$$

The accumulation of energy in the zeolite is a function of conductive and convective heat transport, the amount of energy involved in adsorption/desorption and the energy exchange with the air:

$$\rho_s cp_s \frac{dT_s}{dt} = k_s \nabla^2 T_s - F_s \rho_s cp_s \nabla T_s \pm \begin{bmatrix} \textit{adsorption} \\ \textit{desorption} \end{bmatrix} \textit{heat} \pm \textit{heat transfered} \tag{3}$$

The accumulation of energy in air is a function of conductive and convective heat transport and the energy exchange with the zeolite:

$$\rho_a cp_a \frac{dT_a}{dt} = k_a \nabla^2 T_a - F_a \rho_a cp_a \nabla T_a \mp \textit{heat transfered} \tag{4}$$

Equations 1 to 4 are the basis for the formulation of the full model for each unit in the process. All balances are given in equations A.1 to A.27, in Appendix 5.

3.3. Equipment dimensions, boundary and initial conditions

The dimensions and operation conditions are chosen in such way that the applied conditions are comparable with previous work of Djaeni et al.[5] The equipment considered in the calculations concerns four adsorbers and four drying stages with a total length of 2 m (i.e. 0.5 m/stage), the height of adsorbent bed is 0.2 m and the same value for the height is taken for the dryer, the width for dryer and adsorber is 0.5 m. For the regenerator a length of 2 m is chosen, a height of 0.2 m, and also a width of 0.5 m.

The CFD model for dryer and adsorber is realized by two connected layers: the lower layer represents the adsorber and the upper layer the dryer. Air is not mixed between the adsorber and dryer. The exhaust air from a dryer stage and which is fed to the next adsorber stage is mixed. The CFD-model for the regenerator is realized by a separate unit which is fed by the zeolite from the adsorber, and heated air. The air flow for regeneration is 80% of the air flow through the adsorber and dryer.

The boundary conditions for each stage are given in Table A-1, Appendix 5. For the calculations constants process parameters and the initial conditions depicted in Table A-2 and Table A-3, are used (see Appendix 5). The operation conditions for each stream are given in Table A-4, Appendix 5.1.

3.4. Energy efficiency

The standard definition for energy efficiency of drying processes is the ratio between the heat required to evaporate water from the product and the total heat used in the system:

$$\eta = \frac{Q_{evap}}{Q_{req}} 100\% \tag{5}$$

$$Q_{evap} = F_p (q_{w,d}^{in} - q_{w,d}^{out}) \Delta H_v \tag{6}$$

The required heat (Q_{req}) corresponds to the sum of heat needed to heat ambient air which is fed to the adsorber ($Q_{ad,1}^{in}$) and the heat needed to heat the air for the regenerator (Q_r^{req}) minus the total heat that is recovered.

$$Q_{req} = Q_{ad,1}^{in} + Q_r^{req} - Q_{rec} \tag{7}$$

$$Q_{ad,1}^{in} = F_{a,ad}(cp_a + cp_v q_{v,ad}^{in})(T_{a,ad}^{in} - T_{amb}) \tag{8}$$

Fresh air for the regenerator is pre-heated by air leaving the regenerator. The temperature level of the preheated air is 10°C below the temperature at the outlet of the regenerator (using minimum driving force for heat transfer 10°C).[14] The preheated air is then heated further to the required temperature level for regeneration. The remaining heat to heat up air entering regenerator (Q_r^{req}) is given by:

$$Q_r^{req} = F_{a,r}(cp_a + cp_v q_{v,r}^{in})(T_{a,r}^{in} - T_{a,r}^{out} - 10) \tag{9}$$

Heat recovery is calculated from the amount of zeolite that leaves the regenerator and the required inlet adsorber temperature, as follow:

$$Q_{rec} = F_z(cp_z + cp_w q_{w,r}^{out})(T_{z,r}^{out} - T_{z,ad}^{in}) \tag{10}$$

3.5. Simulation method

Equations A.1-A.27 in Appendix 5, which are partial differential equations, were solved with COMSOL, whereas the remaining equations for efficiency calculation (5-10) were processed separately in Excel. The calculations with COMSOL concern a dynamic model and give the development of the profiles in time and the steady-state profile in the system. The results in this work concern the steady-state profiles.

4. Results and Discussion

4.1. Vapor and air temperature profiles in adsorber and dryer

Figures 5.5 presents the distribution of vapor and temperature of air in the adsorber and dryer for the multistage dryer with a continuous moving bed of zeolite (CMBZ-DRYER), Figure 5.6 for multistage dryer with a discrete bed of zeolite (DBZ-dryer) .

The adsorber, where vapor in the air is adsorbed by the zeolite, has the opposite temperature and vapor content profiles as the dryer where water evaporates from the product. In the first adsorber the vapor content in the air decreases in the direction of the air flow (y-direction). At the output of the first adsorber (y=0.2 m), about 70% of the initial vapor content in the air is removed (see Figure 5.5 part a). This result is below the aimed design value of 80-90% due to:

1. In steady-state operation of the total system, the recycled zeolite fed to the first adsorber is not totally free of water (containing 0.02 kg water/kg zeolite, see also Figure 5.7) and as a result the driving force for adsorption is reduced.

2. Air flow of 1091 kg/hr (1.2 m/sec without porosity) is high for an adsorber bed of 0.2 m diameter. As a result the contact time between the zeolite and air is not sufficient. The dehumidification efficiency can be increased by a thicker layer of zeolite and by lowering the linear air velocity.

Adsorption releases heat which results in a temperature increase of the air over the adsorber (see Figure 5.5 part b). The air at the top of the adsorber has a temperature of 70°C, which is 5-6˚C below the temperature of the zeolite at the same position.

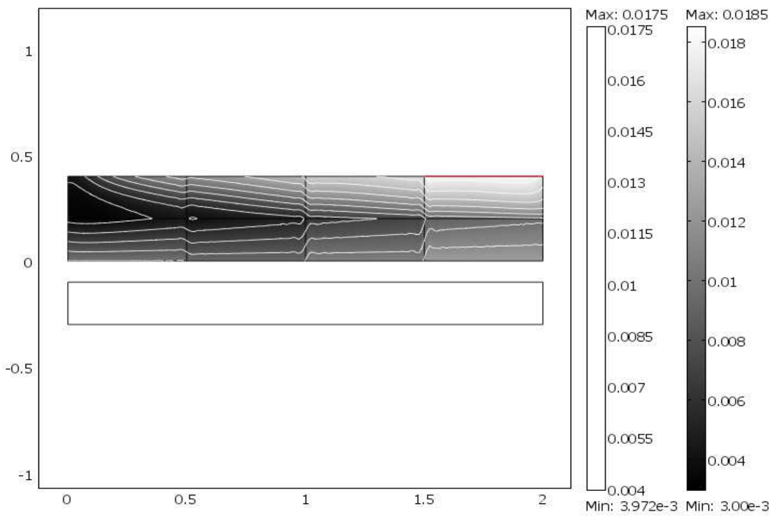
Leaving the first adsorber the air enters the dryer where the vapor content of the air increases due to drying. The temperature of the air declines since the sensible heat is used to heat the product and to evaporate water from the product. As a result, at the top of dryer, the vapor content in the air is the highest and temperature the lowest.

In the following adsorbers (2, 3, 4) the air that leaves the previous drying stage contacts the zeolite and here the vapor content decreases again and the temperature increases. In the dryer with a continuous moving bed of zeolite (CMBZ-dryer) the air contacts zeolite from a previous adsorber stage. The gradually increasing vapor content over the succeeding adsorber stages causes a decreasing driving force for adsorption. As a result, the vapor uptake from the air is below that of stage 1. Another consequence is a lower release of heat in the succeeding adsorber stages and thus the temperature for drying decreases over the succeeding stages. At the last stage the temperature of the air leaving the last adsorber stage is about 35-40°C.

The gradually decreasing temperatures and increasing air moisture content after each adsorber stage affect the drying efficiency in the succeeding drying stages. The increased relative humidity of the air gives a higher value for the equilibrium moisture content of the product (see equation A-16) and thus a lower driving force for drying. For thicker layers vapor uptake is higher.

For the dryer with a discrete bed of zeolite (DBZ-dryer), the results are different (see Figure 5.6). Now the air contacts for every stage fresh zeolite with a low water content. The driving force is now higher than that for the CMBZ-dryer. The dehumidification efficiency over all adsorption stages is better and temperature increases. Air leaving each adsorber has always a temperature above 50°C. However, it must be noted that the performance of adsorber decreases with the stage number. This outcome is result of the gradual increasing vapor content of the air over the succeeding stages.

For the CMBZ-dryer and DBZ-dryer systems, the efficiency differs for each stage. The first stage with the highest temperature of air and the lowest zeolite moisture content has the best performance for adsorption and drying. The performance, however, declines with the stage number. For the applied conditions and referring to Figure 5.5 and 5.6 a 2-3 stage adsorption and drying is most efficient.



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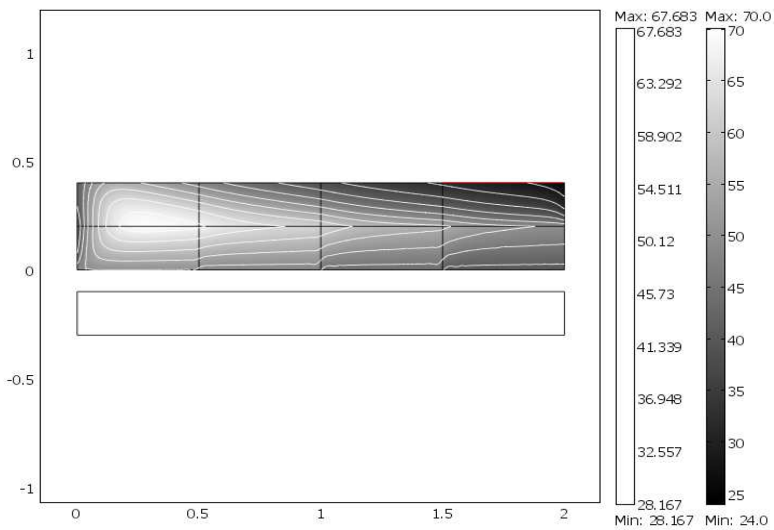
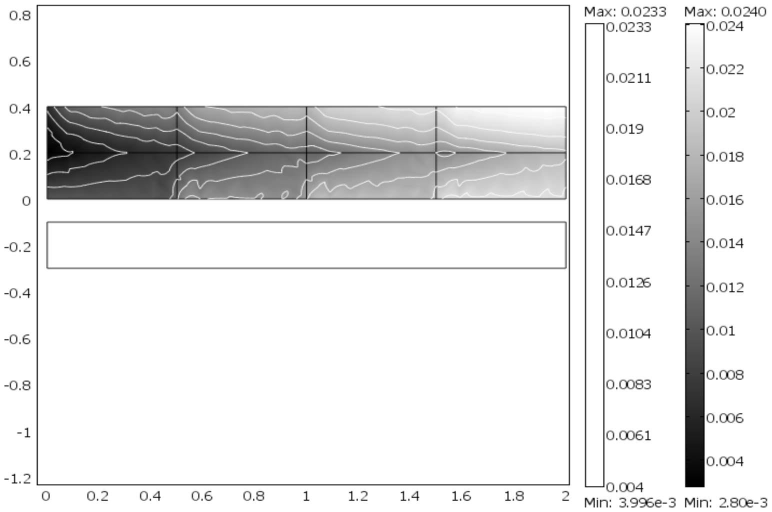


b.

Figure 5.5: Vapor and air temperature distributed in multistage dryer with a Continuous Moving Bed of Zeolite (CMBZ-dryer) where part a is for vapor and part b is for air temperature; CMBZ-dryer at $y = 0 - 0.2$; multi stage dryer for $y = 0.2 - 0.4$



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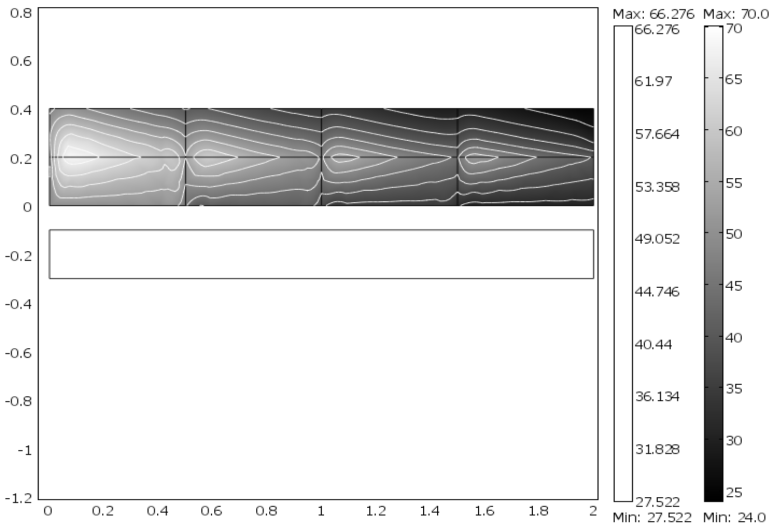


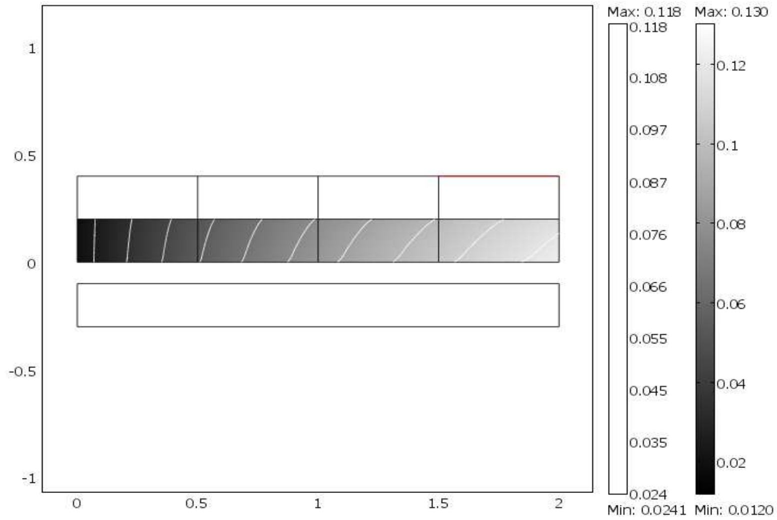
b.

Figure 5.6: Vapor and air temperature distributed in multistage dryer with a Discrete Bed of Zeolite (DBZ-dryer) where part a is for vapor and part b is for air temperature; DBZ-dryer at $y = 0 - 0.2$; multi stage dryer for $y = 0.2 - 0.4$

4.2. Distribution of water in zeolite for adsorber

The water content and temperature profiles over the adsorber units in the CMBZ-dryer with the zeolite flow 120 kg/hr (dry basis) and total length of adsorber 2.0 m are given in Figure 5.7. Figures 5.8 gives the water content and temperature of DBZ-dryer with a zeolite flow of 30 kg/hr and adsorber length 0.5 m per stage. The pattern for the other adsorbers are similar.

The CMBZ-dryer and DBZ-dryer systems have a comparable residence time of the zeolite. For both systems the zeolite water content at the exit of the last adsorber achieves with 0.12-0.13 kg water/kg dry zeolite. This value is 60-65% of the maximum zeolite capacity (0.2 kg water/kg dry zeolite). A higher degree of saturation can be achieved by using a lower zeolite flow. However, then stage 3 and 4 become less efficient, since the driving force for adsorption decreases when the water content in zeolite comes closer to equilibrium.



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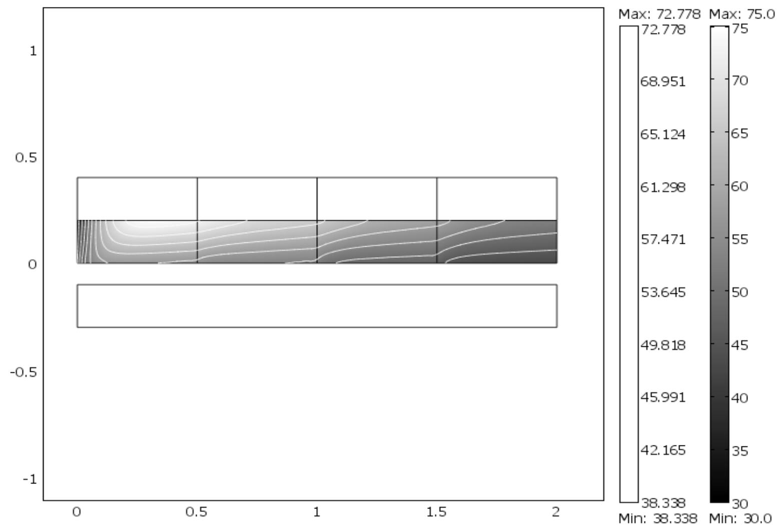
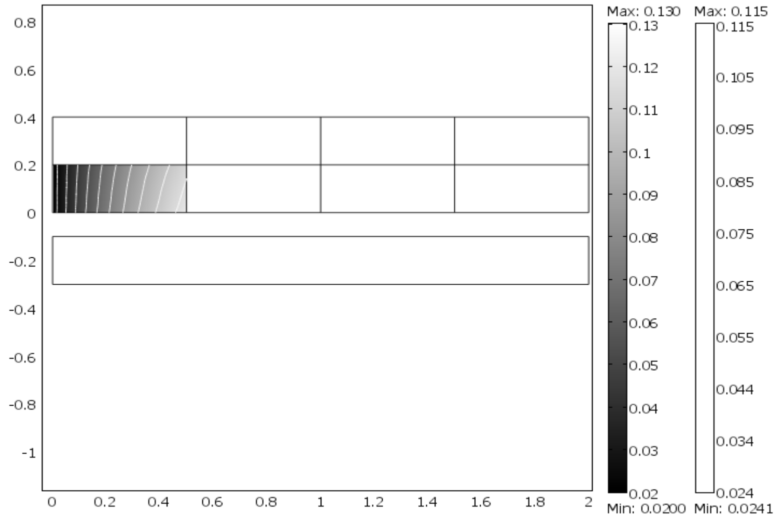


b.

Figure 5.7: Water content and temperature of the Continuous Moving Bed of Zeolite (CMBZ-dryer) where part a is for water content and part b is for bed temperature; CMBZ –dryer at $y = 0 - 0.2$; multi stage dryer for $y = 0.2 - 0.4$



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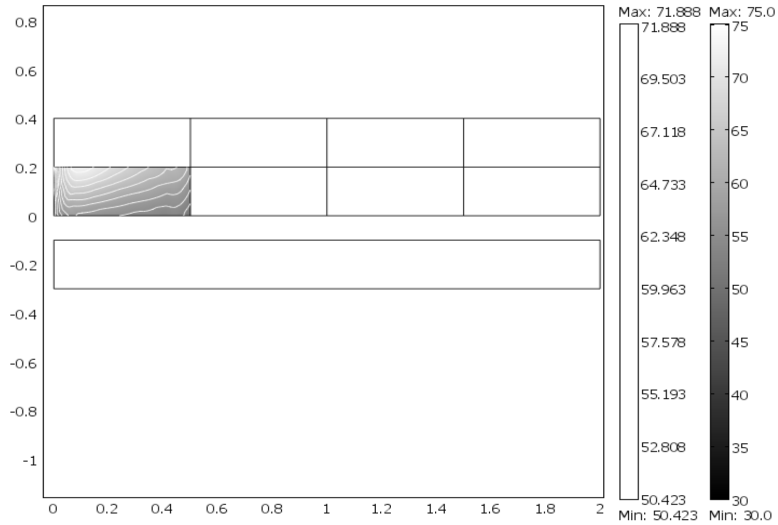
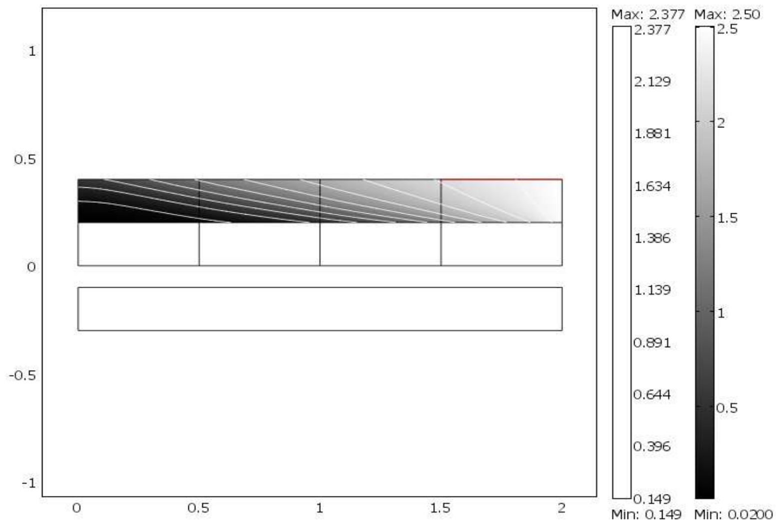


b.

Figure 5.8: Water content and temperature of the Discrete Bed of Zeolite (DBZ-dryer) where part a is for water content and part b is for bed temperature; DBZ-dryer at $y = 0 - 0.2$; multi stage dryer for $y = 0.2 - 0.4$

4.3. Distribution of water in product for dryer

Figures 5.9 and 5.10 present the profiles for the product water content and temperature of product in the dryer for both systems (CMBZ-dryer and DBZ-dryer) with counter current flow of zeolite and product (product from right to the left, and zeolite in the opposite direction). In stage 1, product contacts air with the lowest amount of water and the highest temperature. This make that in stage 1, despite the foregoing drying stages for the product (4, 3 and 2), the driving force for drying is the highest. Consequently, stage 1 is the most efficient one. In stage 4, 3 and 2 drying is less efficient, since in these stages the water content of the air is higher and the temperature lower. As a result the driving force and drying rate go down in these stages. The product water content distribution is not as homogenous as in the zeolite. This means that the drying rate decreases with the height in the dryer



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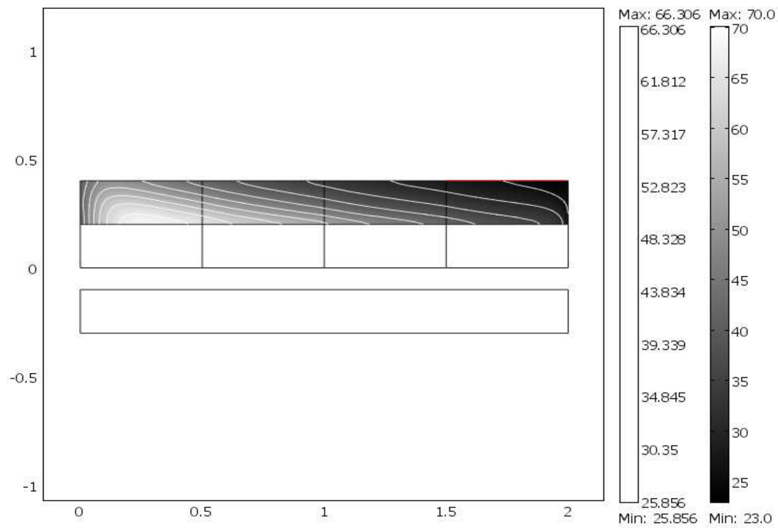
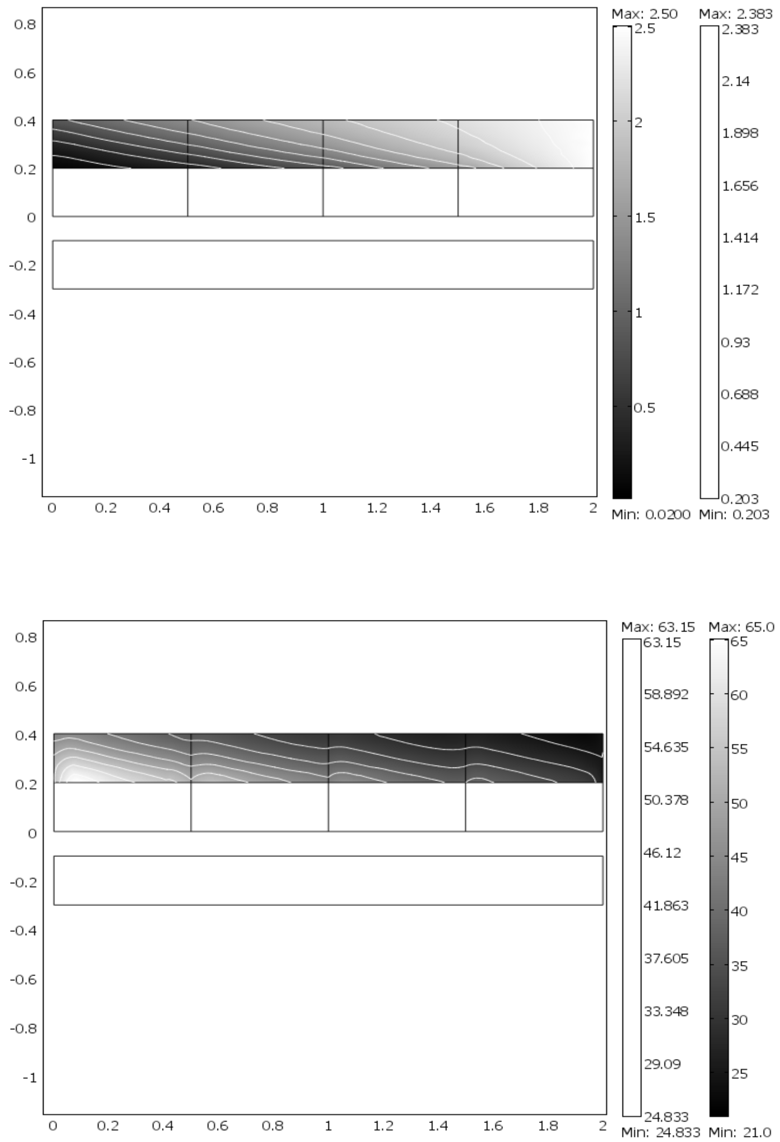


b.

Figure 5.9: Water content and temperature of product for multistage dryer with a Continuous Moving Bed of Zeolite (CMBZ-dryer) where part a is for water content and part b is for bed temperature; CMBZ-dryer at $y = 0 - 0.2$; multi stage dryer for $y = 0.2 - 0.4$



a.

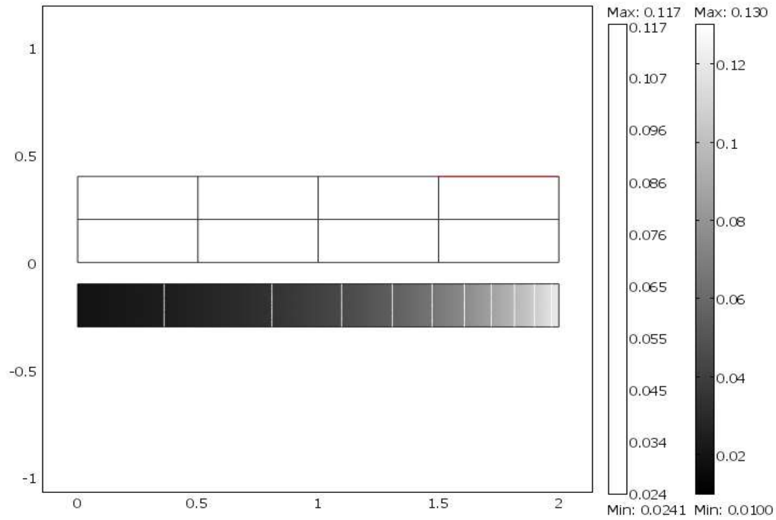
b.

Figure 5.10: Water content and temperature of product for multistage dryer with a Discrete Bed of Zeolite (DBZ-dryer) where part a is for water content and part b is for bed temperature; DBZ-dryer at $y = 0 - 0.2$; multi stage dryer for $y = 0.2 - 0.4$

4.4. Distribution of temperature and water content in the regenerator

The regenerator is used to remove water from spent zeolite and this unit is in fact a dryer. However, in this unit high temperatures (exhaust temperatures should be above 120°C for efficient water removal) are applied. In the considered systems the air and zeolite are transported in the same direction from the right to the left. For our calculations ambient air is heated up to 285°C to ensure that the whole regeneration system is kept above 120°C. Zeolite leaving the adsorber with a water content between 0.12-0.13 kg water/kg zeolite is fed into regenerator.

Figures 5.11 and 5.12, give the distribution of water content and temperature of zeolite temperature in regenerator for multistage dryer with CMBZ-dryer and DBZ-dryer, respectively. The results for the discrete cycle adsorber system are similar because the regeneration system is based on the same method.



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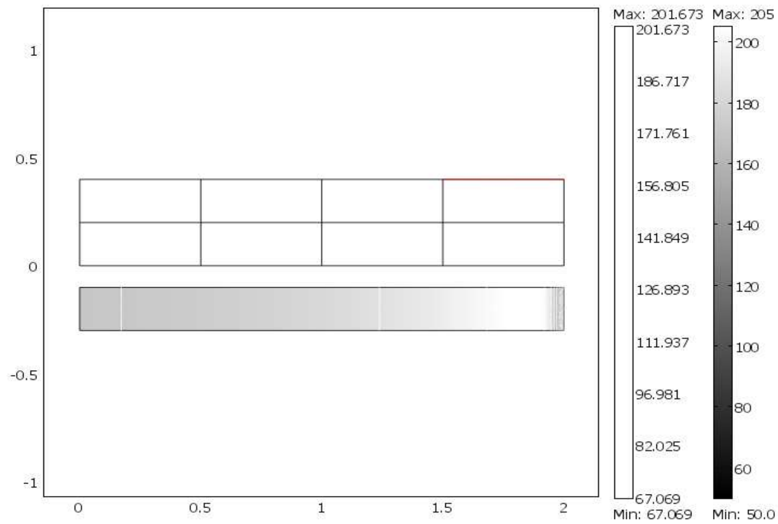
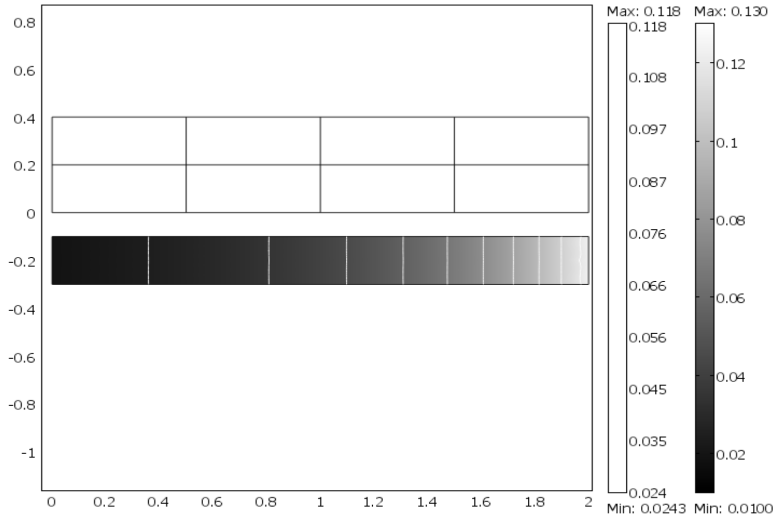


b.

Figure 5.11: Water content and temperature of zeolite in regenerator for a Continuous Moving Bed of Zeolite (CMBZ-dryer) where part a is for water content and part b is for bed temperature



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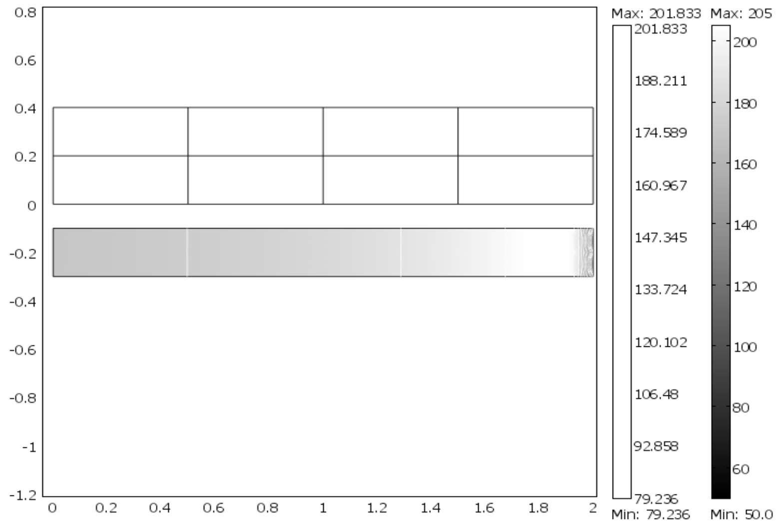

b.

Figure 5.12: Water content and temperature of zeolite in regenerator for a Discrete Bed of Zeolite (DBZ-dryer) adsorber where part a is for water content and part b is for bed temperature

The temperature of the zeolite increases in the first centimeters of the regenerator, reaches a maximum and goes down in the transport direction. In the first centimeter, the hot air is at highest temperature, and sensible heat of hot air is only used for heating up zeolite. While, at the next position corresponding to transport direction, the heat is for heating zeolite and evaporating water in zeolite that cause air temperature become lower than that of first centimeter. As a consequence, the temperature of zeolite also decreases proportional with hot air temperature (as heat source). In this case, using overall heat transfer coefficient from literature[15], the temperature of zeolite at transport direction can close to hot air temperature. The results also showed that the zeolite and air temperatures at the exit of the regenerator are above 160°C, which indicates that regeneration runs well. The water content in the zeolite reduces about 80% from inlet value and ends at the 0.02 kg water/kg dry zeolite. This value corresponds to the inlet value for water content of zeolite fed to the adsorber. Both air and zeolite leaving the regenerator are reused to heat up cold streams of ambient air used for regeneration and drying

5. Discussion

5.1. Comparing the two systems

The continuous moving bed adsorber and discrete cycle adsorber show similar phenomena in terms of their profiles for water content in zeolite, air and product and temperature. Hence, the performance of both systems with respect to energy efficiency is quite close. For the chosen equipment dimensions and operating conditions, the heat efficiency is 90.0% for a multistage dryer with a continuous moving bed of zeolite (CMBZ-dryer), and 89.8% for a discrete bed of zeolite (DBZ-dryer). These results imply that for both cases the total heat used to evaporate water produced from adsorber and the total heat introduced to regenerate zeolite are comparable. It is expected that the construction of the discrete cycle adsorber is more complex than that of the continuous moving bed adsorber. Therefore, the following discussion is focused only on the continuous moving bed adsorber system.

5.2. Energy efficiency

The energy efficiency for counter and co current zeolite dryers obtained for the two dimensional model for the continuous moving bed adsorber is given in Figure 5.13 (dashed line). In the same figure, the results for the lumped overall model used in previous work [5] is given by the lines.

In the counter-current process, the fresh product contacts air from the last adsorber with an increased relative humidity and a low temperature. The fresh product in stage 4 and 3 is somewhat heated which is sufficient to dry the wet product. In the co-current dryer, the product and air move in the same direction. In first dryer stage the product is directly contacted with the air from the first stage adsorber, while for the following stages the product is dried by air from other adsorber stages. The driving force for drying along the stage declines. In stage 4 the drying efficiency is low because of the low drying temperature, high air moisture content and the low moisture in the product. Both models (the two dimensional and steady state model) show that energy efficiency of the co-current dryer is below that of the counter current dryer.

The dryer energy efficiency from the two dimensional counter-current model is close to the results obtained in the previous work. [5] Main reasons for the differences are:

1. heat recovery system in the two dimensional model uses a slightly different direct match since in this case, only two heat exchangers are used for heat recovery [1]

2. steady-state lumped model uses fresh zeolite in every stage, while in the current system the zeolite in the adsorber zeolite comes from a previous stage which results in a lower effectiveness for adsorption.

3. In previous work the zeolite fed to the adsorber was water free and full saturation was assumed after adsorption, while in this case zeolite is not completely free of water. But after taking into account heat released from adsorption and heat required for regeneration, the total efficiency can be comparable

4. In the two dimensional system, the equilibrium sorption-isotherm is a function of the bed height, whereas at previous model[5] the bed height was not included.

For the counter current zeolite dryer, the effects are negligible. The energy efficiency for the two dimensional co-current model is slightly below that of the steady-state lumped model.

The number of stages has a strong effect on system performance. For the counter-current system the efficiency increases from 80-90% by extending stage the number of stages from 2 to 4. For the co-current system, the efficiency does not change above 3 stages.

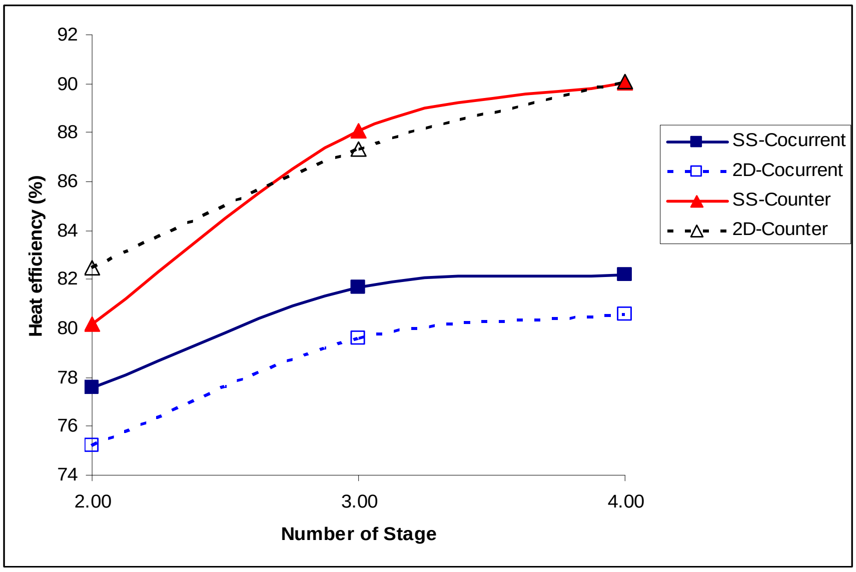

Figure 5.13: Estimated energy efficiency for counter and co-current systems for a different number of stages. Comparing results form the lumped and two dimensional models.

The applied operational conditions for the applied equipment dimensions yield a total product residence time (70-75 minutes) which is comparable to experimental results for drying tarragon leafs which need 75-90 minutes (Arabhosseini et al. [12]). The residence time of zeolite is about 65 minutes and the residence time of air dryer for one stage of adsorption and drying is about 0.006 minutes. So, the total residence time of air is around 0.024 minutes. Using these data, for further application, the dimension of equipments can be estimated corresponding to the product capacity.

5.3. The effect air to product ratio

The system has 33 equations (27 from equations A.1 to A.27, and 6 from equations 5 to 10) with 33 dependent variables and 12 independent variables (see Table A-3). So, there are many possibilities to optimize the system. This discussion on optimization potential is here restricted to the air to product ratio as design variable.

Figure 5.14 shows the results of efficiency calculations for a counter current dryer for which the flow of product is varied from 15 to 27.5 kg/hr (50-90 kg/hr wet basis) while the air flow is kept constant at 1091 kg/hr. The maximum efficiency (88-90%) is achieved at an air to product ratio around 14-15 kg air/kg wet product or water carried capacity 0.035 kg water/kg air. The value is higher to other dryers given in literatures which range from 0.003 to 0.025 depending on type of dryer and product (Arabhosseini, 0.003;[16] Krokida and Bisharat, 0.025;[17] Holmberg and Ahtila, 0.01;[18] Baker et al, 0.025;[19] and Temple, 0.017[20]).

For the adsorption dryers using zeolite, higher air to product ratios are not effective since the air is not able to take more water from the product. If the air to product ratio falls below 14 the product is not enough heated. As a consequence the air temperature is lower, the product equilibrium water content goes up and thus the driving force for drying and drying rate decreases.

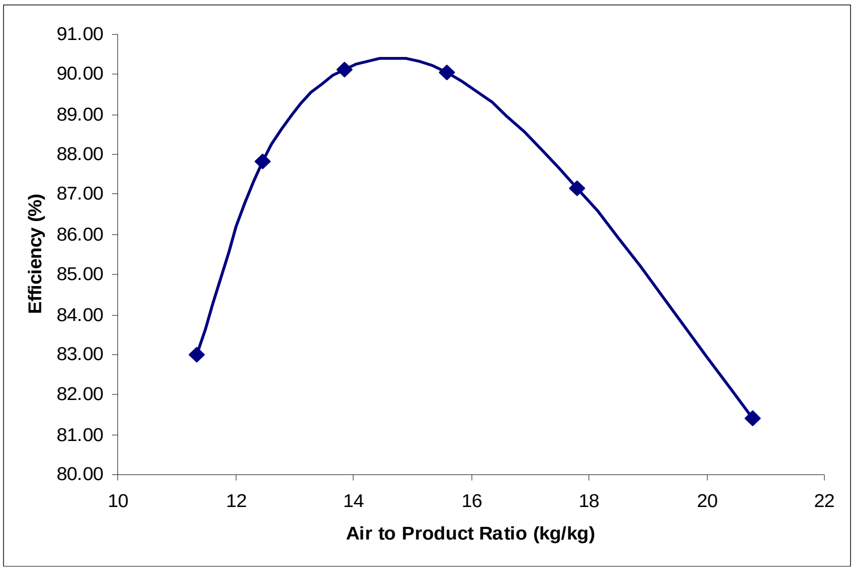

Figure 5.14: Effect of air to product ratio on the energy efficiency at ratio of air drying flow to air regeneration flow 4:1

6. Conclusion

Steady-state mass balance calculations for a multistage adsorption dryer using zeolites, presented in a previous study of Djaeni et al [5], were based on an overall model. In those calculations equipment dimensions were not included and knowledge about the product kinetics was not used. Moreover, such an overall model assumes that the spatial distribution has no effect on the mass and heat transport.

To take the next step ahead in the specification of the dryer dimensions and to incorporate the drying and adsorption/desorption kinetics CFD calculations were performed for a combined adsorber-dryer-regenerator system. The calculations showed:

1. The two-dimensional CFD model gives the internal temperature and water content distribution of all units (dryer, adsorber and regenerator) and reveals characteristic phenomena.
2. The energy efficiency obtained from the CFD calculations is close to the results obtained from the overall steady state model. However, the CFD calculations reveal relevant additional information about temperature and water content profiles. These profiles make it possible to understand the internal phenomena, to find bottlenecks and to improve the design.
3. The continuous moving bed adsorber dryer and the discrete cycle adsorber dryer have comparable energy efficiency performance. The construction of the continuous moving bed adsorber might be less complicated than that of the discrete cycle adsorber and can be preferred for this reason.
4. The amount of vapor adsorbed in the adsorber and the amount of water evaporated in the dryer is influenced by the height of the equipment. The height of the adsorber material is an important variable in design because it results in more water adsorption and, as a result the capacity and the water uptake rate of the dryer improve.
5. The quantity of water that can be adsorbed and the quantity of water removed from the product is affected by the lengths of the adsorber and dryer. It results in a maximum of effective stages. For the proposed capacity and the considered product, 2-3 stages satisfy.

The CFD calculations are powerful to estimate the dimensions and type of equipment for industrial applications of multistage drying. The technical realization and operation of a multistage dryer with a continuous moving bed of zeolite (CMBZ-dryer) is feasible.

Acknowledgement

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Appendix 5

A.1. Adsorber

Water in Zeolite :

$$\frac{dq_{w,ad}}{dt} = D_w \nabla^2 q_{w,ad} - F_z \nabla q_{w,ad} + r_{ads} \quad \text{(A.1)}$$

Water in air:

$$\frac{dq_{v,ad}}{dt} = D_v \nabla^2 q_{v,ad} - F_a \nabla q_{v,ad} - r_{ads} \quad \text{(A.2)}$$

Temperature in zeolite bed:

$$\rho_z cp_{z,ad} \frac{dT_{z,ad}}{dt} = k_z \nabla^2 T_{z,ad} - F_z \rho_z cp_{z,ad} \nabla T_{z,ad} + \Delta H_{ads} \rho_z r_{ads} - U_{ad} (T_{z,ad} - T_{a,ad}) \quad \text{(A.3)}$$

Temperature of air in bed:

$$\rho_a cp_{a,ad} \frac{dT_{a,ad}}{dt} = k_a \nabla^2 T_{a,ad} - F_a \rho_a cp_{a,ad} \nabla T_{a,ad} + U_{ad} (T_{z,ad} - T_{a,ad}) \quad \text{(A.4)}$$

Water adsorption rate:

$$r_{ads} = k_{ads} (q_{e,ad} - q_{w,ad}) \quad \text{(A.5)}$$

with [11]

$$k_{ads} = A_{ads}\, exp(-\frac{E_{ads}}{R} \frac{1}{T_{a,ad} + 273.15}) \quad \text{(A.6)}$$

and $q_{e,ad}$ the equilibrium moisture for zeolite which is a function of air relative humidity (*RH*) and temperature (*T*) according the modified Oswin equation:

$$q_{e,ad} = (C_0 + C_1 T_{a,ad})(\frac{RH_{ad}}{1 - RH_{ad}})^{C_2} \quad \text{(A.7)}$$

C_0, C_1, C_2 are obtained by fitting experimental data (see Table A-2).[12,13]
The heat capacities of air and zeolite in adsrober are:

$$cp_{a,ad} = cp_a + cp_v q_{v,ad} \quad \text{(A.8)}$$

$$cp_{z,ad} = cp_z + cp_w q_{w,ad} \quad \text{(A.9)}$$

A.2. Dryer

Water in product:

$$\frac{dq_{w,d}}{dt} = D_w \nabla^2 q_{w,d} - F_p \nabla q_{w,d} - r_{dry} \quad (A.10)$$

Vapour in air:

$$\frac{dq_{v,d}}{dt} = D_v \nabla^2 q_{v,d} - F_a \nabla q_{v,d} + r_{dry} \quad (A.11)$$

Temperature of product in dryer:

$$\rho_p cp_{p,d} \frac{dT_{p,d}}{dt} = k_p \nabla^2 T_{p,d} - F_p \rho_p cp_{p,d} \nabla T_{p,d} - \Delta H_v \rho_p r_{dry} + U_d (T_{a,d} - T_{p,d}) \quad (A.12)$$

Temperature of air in dryer:

$$\rho_a cp_{a,d} \frac{dT_{a,d}}{dt} = k_a \nabla^2 T_{a,d} - F_a \rho_a cp_{a,d} \nabla T_{a,d} - U_d (T_{a,d} - T_{p,d}) \quad (A.13)$$

where

$$r_{dry} = k_{dry} (q_{e,d} - q_{w,d}) \quad (A.14)$$

For the drying rate coefficient (k_{dry}) and equilibrium moisture content cited form Arabhosseini are used in the following equations [12]

$$k_{dry} = A_{dry} \exp(C_{dry} T_{a,d}) \quad (A.15)$$

$$q_{e,d} = (C_3 + C_4 T_{a,d}) \left(\frac{RH_d}{1 - RH_d}\right)^{C_5} \quad (A.16)$$

The heat capacities for product and air in dryer are:

$$cp_{p,d} = cp_p + cp_w q_{w,d} \quad (A.17)$$

$$cp_{a,d} = cp_a + cp_v q_{v,d} \quad (A.18)$$

A.3. Regenerator

The mass and heat transport in the regeneration section are the opposite of that in the adsorber section. However, some characteristic properties are related to the specific high temperature conditions in the regenerator.

Water in zeolite:

$$\frac{dq_{w,r}}{dt} = D_w \nabla^2 q_{w,r} - F_z \nabla q_{w,r} - r_{des} \quad (A.19)$$

Water in air:

$$\frac{dq_{v,r}}{dt} = D_v \nabla^2 q_{v,r} - F_{ar} \nabla q_{v,r} + r_{des} \quad (A.20)$$

Temperature of zeolite:

$$\rho_z cp_{z,r}\frac{dT_{z,r}}{dt}=k_z\nabla^2 T_{z,r}-F_z\rho_z cp_{z,r}\nabla T_{z,r}-\Delta H_{des}\rho_z r_{des}+U_{des}(T_{ar,r}-T_{z,r})\quad \text{(A.21)}$$

Temperature of air:

$$\rho_a cp_{a,r}\frac{dT_{ar,r}}{dt}=k_a\nabla^2 T_{ar,r}-F_{ar}\rho_a cp_{a,r}\nabla T_{ar,r}+U_{des}(T_{ar,r}-T_{z,r})\quad \text{(A.22)}$$

where

$$r_{des}=k_{des}(q_{e,r}-q_{w,r})\quad \text{(A.23)}$$

$$k_{des}=A_{des}\exp\left(-\frac{E_{des}}{R}\frac{1}{T_{ar,r}+273.15}\right)\quad \text{(A.24)}$$

The desorption rate constant equals to adsorption rate constants ($A_{des}=A_{ads};E_{des}=E_{ads}$, see equation A.6). The equilibrium moisture is for temperatures above 100°C is given by the modified Oswin equation.[12,13]

$$q_{e,r}=(C_6+C_7T_{a,r})\left(\frac{RH_r}{1-RH_r}\right)^{C_8}\quad \text{(A.25)}$$

The heat capacities of air and zeolite in regenerator are:

$$cp_{a,r}=cp_a+cp_v q_{v,r}\quad \text{(A.26)}$$

$$cp_{z,r}=cp_z+cp_w q_{w,r}\quad \text{(A.27)}$$

Table A-1: Boundary conditions for the counter current dryer

Parameter		Coordinate x	Coordinate y	Expression
Adsorber & Dryer		**x**	**y**	
Air	$q_{v,ad}, T_{a,ad}$	0	0 to h_{ad}	$\frac{dq_{v,ad}}{dx}=0$; $\frac{dT_{a,ad}}{dx}=0$
	$q_{v,d}, T_{a,d}$	0	h_{ad} to h_d	$\frac{dq_{v,d}}{dx}=0$; $\frac{dT_{a,d}}{dx}=0$
	$q_{v,ad}, T_{a,ad}$	0 to l_d	0	$-\frac{dq_{v,ad}}{dy}+F_a q_{v,ad}=F_a q_{v,d}^{i-1}$; $-k_a\frac{dT_{a,ad}}{dy}+Q_{a,ad}=Q_{a,ad}^{in,i}$ $Q_{a,ad}=F_a\rho_a cp_{a,d}T_{a,ad}$; $Q_{a,ad}^{in,i}=F_a\rho_a cp_{a,d}^{i-1}T_{a,d}^{i-1}$; i=1,2,3..; for i=1: $cp_{a,d}^{i-1}=cp_{a,ad}^{in}$; $T_{a,d}^{i-1}=T_{a,ad}^{in}$;
	$q_{v,ad}, T_{a,ad}$ $q_{v,d}, T_{a,d}$	0 to l_d	h_{ad}	$\frac{dq_{v,ad}}{dy}=0$; $\frac{dT_{a,ad}}{dy}=0$; $q_{v,d}=q_{v,ad}$; $T_{a,d}=T_{a,ad}$
	$q_{v,d}, T_{a,d}$	0 to l_d	h_d	$q_{v,d}\vert_{out}=q_{v,d}\vert_{y=h_d}$; $T_{a,d}\vert_{out}=T_{a,d}\vert_{y=h_d}$
	$q_{v,ad}, T_{a,ad}$	l_d	0 to h_{ad}	$\frac{dq_{v,ad}}{dx}=0$; $\frac{dT_{a,ad}}{dx}=0$
	$q_{v,d}, T_{a,d}$	l_d	h_{ad} to h_d	$\frac{dq_{v,d}}{dx}=0$; $\frac{dT_{a,d}}{dx}=0$
Zeolite	$q_w; T_z$	0	0 to h_{ad}	$-\frac{dq_{w,ad}}{dx}+F_z q_{w,ad}=F_z q_{w,ad}^{in}$; $q_{w,ad}^{in}=q_{w,r}^{l_r}$; $-k_z\frac{dq_{z,ad}}{dx}+Q_{z,ad}=Q_{z,ad}^{in}$; $Q_{z,ad}=F_z\rho_z cp_{z,ad}T_{z,ad}$; $Q_{z,ad}^{in}=F_z\rho_z cp_{z,ad}^{in}T_{z,ad}^{in}$
	$q_w; T_z$	l_d	0 to h_{ad}	$q_{w,ad}\vert_{out}=q_{w,ad}\vert_{x=l_{ad}}$; $T_{z,ad}\vert_{out}=T_{z,ad}\vert_{x=l_{ad}}$
	$q_w; T_z$	0 to l_d	0 or h_{ad}	$\frac{dq_{w,ad}}{dx}=0$; $\frac{dT_{z,ad}}{dx}=0$
Product	$q_w; T_p$	0	h_{ad} to h_d	$q_{w,d}\vert_{out}=q_{w,d}\vert_{x=0}$; $T_{p,d}\vert_{out}=T_{p,d}\vert_{x=0}$ (co-current at $x=l_d$)
	$q_w; T_p$	l_d	h_{ad} to h_d	$-\frac{dq_{w,p}}{dx}+F_p q_{w,d}=F_p q_{w,d}^{in}$; $-k_p\frac{dT_{p,d}}{dx}+Q_{p,d}=Q_{p,d}^{in}$ $Q_{p,d}=F_p\rho_p cp_{p,d}T_{p,ad}$; $Q_{p,d}^{in}=F_p\rho_p cp_{p,d}^{in}T_{p,d}^{in}$ (co-current at $x=0$)
	$q_w; T_p$	0 to l_d	h_{ad} or h_d	$\frac{dq_{w,d}}{dy}=0$; $\frac{dT_{p,d}}{dy}=0$
Regenerator		**x**	**y**	
Air Reg.	$q_v; T_{ar}$	0	0 to h_r	$q_{v,r}\vert_{out}=q_{v,r}\vert_{x=0}$; $T_{a,r}\vert_{out}=T_{a,r}\vert_{x=0}$
	$q_v; T_{ar}$	l_r	0 to h_r	$-\frac{dq_{v,r}}{dx}+F_{ar}q_{v,r}=F_{ar}q_{v,d}^{in}$; $-k_a\frac{dT_{a,r}}{dx}+Q_{a,r}=Q_{a,r}^{in}$ $Q_{a,r}=F_{ar}\rho_a cp_{a,r}T_{a,r}$; $Q_{a,r}^{in}=F_{ar}\rho_a cp_{a,r}^{in}T_{a,r}^{in}$
	$q_v; T_{ar}$	0 to l_r	0 & h_r	$\frac{dq_{v,r}}{dy}=0$; $\frac{dT_{ar,r}}{dy}=0$
Zeolite	$q_w; T_z$	0	0 to h_r	$q_{w,r}\vert_{out}=q_{w,r}\vert_{x=0}$; $T_{z,r}\vert_{out}=T_{z,r}\vert_{x=0}$
	$q_w; T_z$	l_r	0 to h_r	$-\frac{dq_{w,r}}{dx}+F_z q_{w,r}=F_z q_{w,ad}^{l_d}$; $-k_z\frac{dT_{z,r}}{dx}+Q_{z,r}=Q_{z,ad}^{l_d}$ $Q_{z,r}=F_z\rho_z cp_z T_{z,r}$; $Q_{z,ad}^{l_d}=F_z\rho_z cp_{z,ad}^{l_d}T_{z,ad}^{l_d}$
	$q_w; T_z$	0 to l_r	0 & h_r	$\frac{dq_{w,r}}{dx}=0$; $\frac{dT_{z,r}}{dx}=0$

$l_r=l_d=l_{ad}$=2 m, $h_{ad}=h_d=h_r$=0.2 m, $w_d=w_{ad}=w_r$=0.5 m

(adsorber coordinates defined as: $x=0$ to l_d, and $y=0$ to h_{ad}; dryer coordinates: $x=0$ to l_d, and $y=h_{ad}$ to h_d, regenerator coordinates: $x=0$ to l_r, and $y=0$ to h_r).

Table A-2: Used value for parameters

Notation	Parameter	Value
A_{ads}	Adsorption rate factor, 1/sec	0.00404
A_{des}	Desorption rate rate factor, 1/sec	0.00404
A_{dry}	Constant of drying rate (1/min)	0.0456/60
C_0, C_1,C_2	Constant moisture equilibrium for zeolite < 100°C	0.24, 0.00, 0.023
C_3, C_4,C_5	Constant moisture equilibrium for tarragon	0.131, -0.0005 , 0.50
C_6, C_7,C_8	Constant moisture equilibrium for zeolite at higher 100°C	0.24, -0.0008, 0.023
cp_a	Specific heat of dry air (kJ/kg ^{o}C)	1.00
cp_v	Specific heat of vapor water (kJ/kg ^{o}C)	1.93
cp_w	Specific heat of liquid water (kJ/kg ^{o}C)	4.20
cp_z	Specific heat of dry zeolite (kJ/kg ^{o}C)	0.84
E_{ads} / R	Activation energy to constant ideal gas ratio, 1/^{o}K	905.8
E_{des} / R	Activation energy to constant ideal gas ratio, 1/^{o}K	905.8
E_{dry}	Constant (1/^{o}C)	0.0665
ΔH_{ads}	Latent heat of water adsorption (kJ/kg)	-3200
ΔH_v	Latent heat of water evporation (kJ/kg)	2500
RH	Relative Humidity, %	
x, y	The direction of x-y, coordinate in height and length	
z_d	The width of bed, m	0.4
ρ_a	Density of dry air, kg/m^3	1.01
ρ_p	Density of dry product, kg/m^3	200
ρ_z	Density of dry zeolite, kg/m^3	1100

Table A-3: Initial conditions for the calculations

Parameter	Initial value at t=0, for all x and y
Water in zeolite adsorber, kg water/kg dry zeolite	$q^0_{w,ad} = q^{in}_{w,ad}$
Temperature of zeolite in adsorber, °C	$T^0_{z,ad} = T^{in}_{z,ad}$
Vapour in air adsorber, kg vapour/kg dry air	$q^0_{v,ad} = q^{in}_{v,ad}$
Temperature of air in adsorber, °C	$T^0_{a,ad} = T^{in}_{a,ad}$
Vapour in air dryer, kg vapour/kg dry air	$q^0_{v,d} = 0.005$
Temperature of air in dryer, °C	$T^0_{a,d} = 50$
Water in product dryer, kg water/kg dry product	$q^0_{w,d} = q^{in}_{w,d}$
Temperature of product in dryer, °C	$T^0_{p,d} = T^{in}_{p,d}$
Water in zeolite regenerator, kg water/kg dry zeolite	$q^0_{w,r} = q^{in}_{w,r}$
Temperature of zeolite in regenerator, °C	$T^0_{z,r} = T^{in}_{z,r}$
Vapor in air regenerator, kg vapour/kg dry air	$q^0_{v,r} = q^{in}_{v,r}$
Temperature of air in regenerator, °C	$T^0_{a,r} = T^{in}_{a,r}$

Table A-4: Conditions for each flow

Parameter	notation	value
Flow of dry zeolite to adsorber, kg/hr	F_z	120
Temperature of zeolite to adsorber, °C	$T_{z,ad}^{in}$	35
Flow of dry air to adsorber/dryer, kg/hr	F_a	1091
Temperature of air to adsorber, °C	$T_{a,ad}^{in}$	25
Vapour in air to adsorber, kg vapour/kg dry air	$q_{v,ad}^{in}$	0.01
Flow of dry zeolite to regenerator, kg/hr	F_z	120
Flow of dry air to regenerator/dryer, kg/hr	F_{ar}	873
Temperature of air to regenerator, °C	$T_{a,r}^{in}$	285
Vapour in air to regenerator, kg vapour/kg dry air	$q_{v,r}^{in}$	0.01
Flow of dry product to dryer, kg/hr	F_p	15-27.5
Temperature of product to dryer, °C	$T_{p,d}^{in}$	25
Water in product to dryer, kg water/kg dry product	$q_{w,d}^{in}$	2.5

Chapter 6

Performance Evaluation of Adsorption Dryer Using Zeolite

Abstract

The potential energy efficiency improvement for single-stage drying with air dehumidification by zeolite is validated experimentally. The experimental results are fitted to a dynamic model which is used to find important variables for the operation of the zeolite dryer. The ratio between air flow for drying and air flow for regeneration affect the energy efficiency significantly, just like the ambient air temperature. Relative humidity of used air and shift time have a minor effect on the dryer performance. The results show that with the single-stage zeolite dryer energy efficiencies of 75% can be achieved.

Keywords: drying, adsorption, regeneration, energy efficiency, zeolite

List of symbols

A	cross sectional area	(m^2)
$C_{1,2,..n}$	equilibrium and kinetic constant	
F	flow of dry component	(kg/min)
G	flow of wet component	(kg/min)
ID	internal diameter	(m)
P	total pressure	(bar)
Q	heat flow	(kJ/min)
R	gas constant	(kJ/kmole K)
RH	relative humidity	(%)
S_{pa}	specific surface area	(m^2/kg)
T	temperature	(^{o}C)
U	overall heat transfer coefficient	(kJ/m^2 min °C)
V	volume	(m^3)
cp	specific heat	(kJ/kg°C)
h	height in adsorbent	(m)
h_{ad}, h_d, h_{reg}	total height of adsorber, dryer, regenerator	(m)
k	constant of water transfer rate	(1/min)
l_d	length of dryer	(m)
q	moisture content in dry matter	(kg moisture/kg dry matter)
r	rate of water transfer	(kg water/kg dry matter/ min)
t	time	(min)
tf	final time	(min)
w_d	width of dryer	(m)
y	vapor in air	(kmole/kmole dry air)
ΔH	latent heat of water change	(kJ/kg)
ρ	density	(kg/m^3)
η	energy efficiency	(%)
ε	porosity of material	

Subscripts

a	air	*ad*	adsorber	*ads*	adsorption
amb	ambient	*c*	cycle	*col*	column
d	dryer	*des*	desorption		
dry	drying	*e*	equilibrium	*evap*	evaporation
in	inlet	*intr*	introduced	*max*	maximum
out	outlet	*p*	product		
reg	regenerator	*rec*	recovery	*req*	required
v	vapour	*w*	water	*z*	zeolite

1. Introduction

The drying capacity of the air to evaporate water from products is related to the relative humidity of the air used for drying, which in turn depends on the vapor content and temperature of the air. The drying capacity increases if the relative humidity decreases. In conventional drying systems, the drying capacity is improved by increasing the air temperature or by decreasing the pressure in order to reduce the relative humidity of air.[1] Both approaches are successful in improving the driving force, but are unfavorable in terms of energy use and have other drawbacks. The first approach is disadvantageous for drying of heat sensitive products for which the maximum drying temperature is a constraint to retain product quality. The second approach requires high investment and operational costs to create the low pressure.

An alternative to improve the drying capacity of air is by removing the vapor in the air used for drying by condensation or by using adsorbents. [2,3,4] Removal of vapor dehumidifies the air and thus improves the driving force for drying. Previous work showed that an adsorption dryer (where air is dehumidified by using adsorbents) has a higher potential for the reduction of energy usage and operational costs than a condensation dryer (where dehumidification based on condensation) or freeze-drying.[2,4] The total costs (fixed and operational cost for energy supply) of an adsorption dryer are about 50% below the total costs for a freeze-dryer [2] and the energy efficiency of an adsorption dryer operated below 50^{o}C is up to 15-20% higher than that of a condensation dryer.[4] For drying at operation temperatures in the range of 60-80^{o}C, the energy usage of adsorption dryer using zeolite can be half of the energy usage of a standard dryer working at comparable conditions.[5,6]

Experimental work has been conducted to study the potential and effectiveness of several solid adsorbents for dehumidifying air to improve the driving force in drying processes. Witinantakit et al[7] tested the performance of paddy (rice) husk as vapor adsorbent in paddy drying and concluded that the drying rate was increased and a lower final paddy moisture content could be achieved by using dehumidified air. Nagaya et al[8] improved the drying rate for vegetables (cabbage, egg plants and carrots) using air dehumidified by silica and could retain product quality attributes as color and vitamin. Revilla et al[9] studied immersion drying of wheat using several adsorbents (alumina pillared clay, sand, and zeolite) to speed up water evaporation, and Alikhan et al[10] evaluated the potential of zeolite as adsorbent for drying corn in a rotary dryer. They found that zeolites have potential to increase the drying rate. Moreover, the capability of zeolites (4Å, 5Å and 13X) to dehumidify air has been tested and the results indicated that the vapor content in air can be reduced till a dew point of -60^{o}C.[11] With this performance zeolite yields a far better dehumidification compared to common adsorbents as silica and alumina, and therefore zeolite is very important for adsorption drying[12]

Despite of the improvement of the drying rate and the release of adsorption heat, spent zeolite needs heat for its regeneration before reuse for air dehumidification. Improvements in the energy efficiency for the drying unit are (partly) cancelled by the energy requirement for regeneration. In the literature there is a lack on information on the effectiveness of zeolite for the dehumidification of air when both heat of regeneration and adsorption are taken into account. At present, only partial studies has been done done: for example characterizing the zeolite systems itself (adsorption-regeneration system)[13] and drying with zeolite to improve the drying rate.[9,10] In other experimental work[9,10] the zeolite was mixed with product which affects the purity of the product making the process less or not suitable for foods and pharmaceutical products. The lack of information has encouraged the authors to study how adsorption-regeneration system could be integrated with the drying unit such that the heat efficiency is improved.

In a preceding design study an integrated system involving adsorber-regenerator, heater, dryer and heat recovery using a compressor and a heat exchanger network has been developed and evaluated with respect to the energy efficiency.[5,6] The systems can be operated as a single-stage or a multistage system. Efficiency improvements between 10-50%, depending on the number of stages, can be realized. Furthermore, the dimensions of adsorber, regenerator and dryer in a continuous operated system were derived with a two dimensional CFD model.[14] Despite the promising results the design concept needs validation by experimental work to prove the effectiveness of adsorption drying using zeolite.

This work is an experimental assessment of the energy efficiency for a single-stage dryer using zeolite for air dehumidification as proposed in previous work. [5] The experimental data is fitted to a dynamic model for the experimental installation, and subsequently the model is used to predict the energy efficiency for a range of operational conditions.

2. Experimental Setup

2.1. Single stage adsorption dryer

Figure 6.1 presents the scheme of the experimental set-up of an adsorption dryer system using zeolite (Ebbens-Engineering the Netherlands). The system uses a fan for air supply and two columns (A and B) each filled with 2.5 kg of synthetic zeolite (siliporite 4Å from CECA, France). The columns with 0.15m internal diameter (ID) and 0.40m height are used alternately as adsorber or regenerator by simultaneous switching of a set three way valves (V1-V4). The valves are operated in such a way that after a period with a given shift time the function of the column is interchanged. The capacity of siliporite to load water is 0.22 kg water/kg zeolite and can reduce the humidity of air to a dew point -50°C.[15] All the connecting pipes in this system had 0.05m internal diameter (ID). The columns and piping are all insulated with 0.03 m thick layer of insulation wool.

HE01 is an electric heater used to heat up air for regeneration. B01 is a non-insulated column (inner diameter 0.15 m and 0.4 m height) to equalize temperature variations that occur after switching between adsorber and regenerator function. The buffer could be filled with alumina grid to make the buffering effect larger, but for the reported experiments the buffer was empty. HE02 is an additional electric heater to heat the dehumidified air from B01 up to the requested inlet dryer temperature. D01 is a tray dryer (cross sectional area 0.3x0.3m and height 0.4 m), where wet products are dried by dehumidified air. For these experiments sponges are used to imitate products which are in a constant drying rate period.

Sensors T-RH 1-3 (type HMP 130Y-O0205-4.3, VAISALA, Finland) are used to measure temperature and relative humidity of the air flows. F1 and F2 are air velocity sensors (SS 20.01/.011/0.12, SCHMIDT Feintechnik, Germany) to measure the linear velocity of air used for adsorption and regeneration. TH1-5 are K-type thermocouples (MB-ISK-S05-150-MP, Labfacility Ltd, United Kingdom) for temperature measurement.

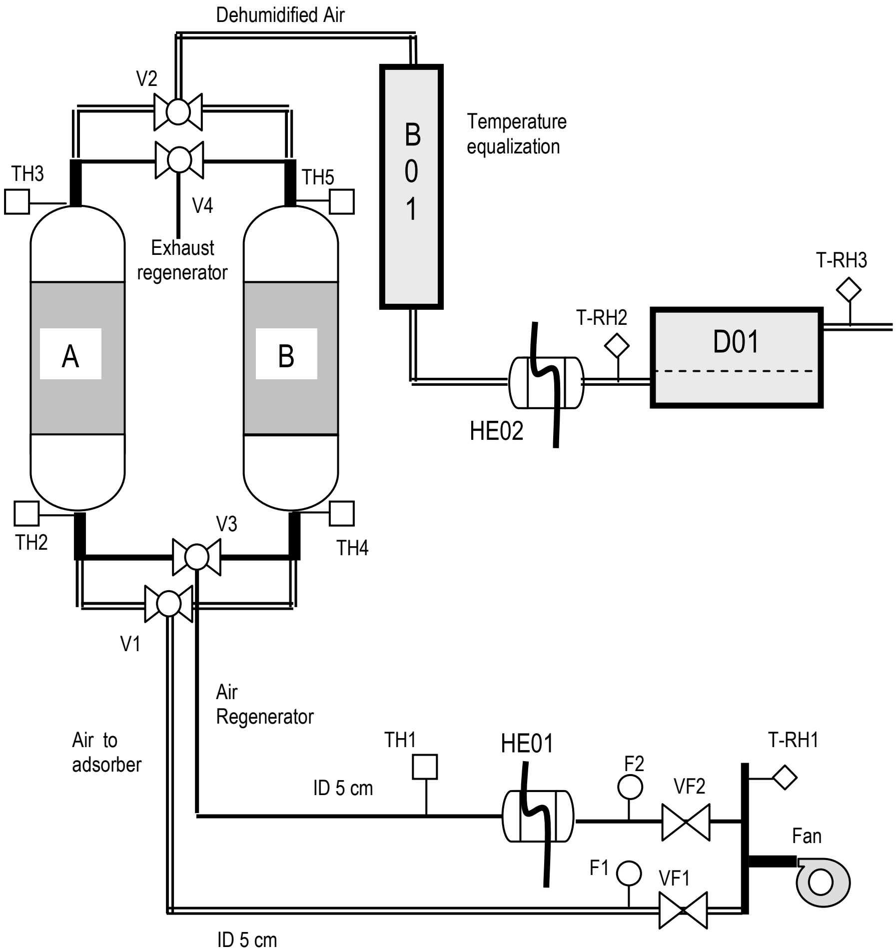

Figure 6.1: Experimental set-up of adsorber-regenerator-dryer system

2.2. Air dehumidification in a twin-column shift system

A fan is used to pass air at ambient conditions through the pipes (see Figure 6.1). The air is divided into two streams. The first stream is fed to the adsorber adjusted by VF1, the other flow adjusted by VF2 enters HE01 and is heated up to above 110°C for the regenerator. In the adsorber (suppose column A), vapor is adsorbed from the air during contacting the zeolite bed, and thereby releasing heat which results a raised temperature leaving column A (TH3 > TH2). Air is then passed though HE02 to reach the drying temperature. Leaving HE02, the dehumidified air enters dryer (D01) to evaporate free water from the wet product.

Meanwhile, the hot air entering column B regenerates the spent zeolite. The hot air flow evaporates water from the saturated zeolite and as a result the outlet temperature of the regenerator is below the inlet temperature (TH5<TH4). The exhaust air from the regenerator is not further used in this system, but from the measured temperature the heat recovery potential is calculated.

At the end of a period with continuous air flow the zeolite in column A will become nearly saturated with water. As a result, the adsorption effectiveness decreases. To continue air dehumidification the air for drying is switched to the column B with dry zeolite, while the saturated zeolite in column A is regenerated. As a consequence, the inlet and outlet point of adsorber-regenerator are also moved from TH2-TH3 to TH4-TH5. The shift time is defined as the time between successive switching instants.

2.3. Data collection

In the experimental system the shift time, temperature of air for dryer and regenerator are manually controlled. The air flow is adjusted by regulating the valve positions VF1 for drying air, and VF2 for regenerator air. A program developed in LABVIEW and running on a PC is used to realize the setting values, to monitor drying, to collect experimental data and as a user interface. The data is recorded every two seconds. The data concerns:

- linear velocity of dryer air and regenerator air (F1 and F2),
- temperature of air entering adsorber and regenerator (TH2 or TH4 depending on shift),
- temperature of air exiting adsorber and regenerator (TH3 or TH5 depending on shift),
- relative humidity and temperature of ambient air (T-RH1),
- air entering and exiting dryer (T-RH2 and T-RH3).

By combining experimental data, the dimension of the pipes and physical properties of the components (air, zeolite, vapor, and water), the mass and energy flow of all the streams were calculated at each sampling moment. The data is used to calculate the energy efficiency of the system as presented in section 2.4.

Data was collected from the start-up of the installation. The first shift is regarded as a start shift for heating the installation and to regenerate the zeolite. From this moment the data is used for energy efficiency calculations, model fitting and validation.

Experiments concerned shift times 30, 45 and 60 minutes. Ambient air was used for the experiments. Temperature and humidity depended on the weather conditions and varied between 17-22°C, and 0.006-0.009 kg water/kg air. The inlet regeneration temperature was set to 140°C.

2.4. Energy efficiency calculation

The heat efficiency of system is calculated as follows:

$$\eta = \frac{Q_{evap}}{Q_{int\,r} - Q_{rec,max}} 100\% \qquad (1)$$

with Q_{evap} as the total heat required for evaporating water in the dryer (kJ) which follows from the inlet and outlet air humidity ($q_{v,d}^{in}, q_{v,d}^{out}$), and the mass flow of dry air through the dryer ($F_{a,d}$). For a total operational time tf, Q_{evap} corresponds to:

$$Q_{evap} = \int_{t=0}^{t=tf} F_{a,d} \Delta H_{evap} (q_{v,d}^{out} - q_{v,d}^{in}) dt \qquad (2)$$

where the values of humidity ($q_{v,d}^{in}, q_{v,d}^{out}$) are derived from the temperature and relative humidity of air recorded over an experiment (T-RH2 and T-RH3). The mass flow of dry air ($F_{a,d}$) is calculated from the recorded air flow according:

$$F_{a,d} = \frac{G_{a,d}}{1 + q_{v,d}^{in}} \qquad (3)$$

with $G_{a,d}$ the mass flow of wet air (kg/minute) derived from the air velocity from F1 measurement multiplied with the cross sectional area of the pipe and air density.

$Q_{int\,r}$ is total of heat introduced to system (kJ) and equals the heat supplied to the regenerator and the heat to bring the dehumidified air from adsorber to the drying temperature:

$$Q_{int\,r} = \int_{t=0}^{t=tf} (F_{a,reg} cp_{a,reg} (T_{a,reg}^{in} - T_{amb}) + F_{a,ad} cp_{a,ad} (T_{a,d}^{in} - T_{a,ad}^{out})) dt \qquad (4)$$

where $F_{a,ad}$ is the dry air flow entering the adsorber. It is equal to $F_{a,d}$. $F_{a,reg}$ is calculated analog to equation 3 using the data from measurement device F2, $T_{a,reg}^{in}$ follows from TH2 or TH4 depending on the shift, T_{amb} and $T_{a,d}^{in}$ are measured by T-RH1 and T-RH2, respectively. Finally, $T_{a,ad}^{out}$ is measured by TH3 or TH5 depending on the shift.

$Q_{rec,max}$ is the calculated amount of heat which could be recovered from the exhaust air of the regenerator (kJ). The recovery is based on a heat exchanger with 10°C temperature difference between hot and cold stream. Using pinch technology as applied in previous work[4,5], the maximum recovered heat is:

$$Q_{rec,max} = \int_{t=0}^{t=tf} F_{a,reg} cp_{a,reg} (T_{a,reg}^{out} - T_{amb} - 10) dt \tag{5}$$

Here, $T_{a,reg}^{out}$ is measured from TH3 or TH5 depending on the shift.

3. Model Development

3.1. Assumptions

The model in the form of partial differential equations is set up to predict the energy efficiency of the zeolite dryer for process conditions which are beyond the experimental range of the installation. The model is based on mass and energy balances for air and solids in the adsorber, regenerator and dryer. Figure 6.2 gives a schematic presentation of the flows. Temperatures for air, zeolite and product, as well as moisture in air, zeolite and product are a function of the vertical dimension (*h*). The balances consider moisture and energy exchange between air and solid material and also heat loss due to temperature differences between the air in the equipment and air in the environment. Moreover, heat released during adsorption and heat required for regeneration is taken into account.

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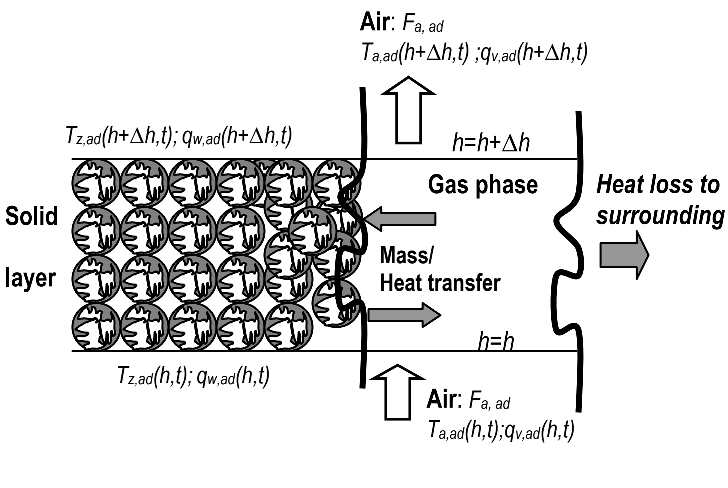


Figure 6.2: Spatial representation for adsorber, regenerator and dryer

The model is based on the following assumptions:

1. the flow of air through the bed of adsorbent is plug flow,
2. pressure drop over the equipment is neglected,
3. physical constants as density, specific heat, and diffusion coefficients are constant,
4. only the dynamics and spatial distribution in the adsorber, dryer and regenerator are considered; responses for heater, and pipes are instantaneous,
5. the free water of imitated product in dryer is in excess and so that the dryer operates in a constant drying rate period,
6. adsorption heat is equal to desorption heat,
7. the model includes heat loss from adsorber, regenerator and dryer to the environment,
8. buffer works quickly and perfectly during the operational time,
9. water and heat transport between zeolite and product particles take place through the air and not by particle contact.

3.2. Model formulation

The model includes the mass balances for liquid water, water vapor, and the heat balances for zeolite, product and air temperature. These balances are based on the laws of conservation for mass and energy. Table 6.1 presents the dynamic mathematical model describing the phenomena in each equipment unit. The model is completed by the additional equations as depicted in Table 6.2.

Table 6.1: Dynamic models of the adsorption dryer system

Adsorber

Mass balance of water

Zeolite: $$\frac{dq_{w,ad}(h,t)}{dt} = r_{ads}(h,t) \quad (6)$$

Air: $$\varepsilon_z \frac{dq_{v,ad}(h,t)}{dt} = -(\frac{F_{a,ad}}{\rho_a A_{col}})\frac{dq_{v,ad}(h,t)}{dh} - \frac{\rho_z}{\rho_a}(1-\varepsilon_z)r_{ads}(h,t) \quad (7)$$

Heat balance

Zeolite: $$\rho_z cp_{z,ad}(1-\varepsilon_z)\frac{dT_{z,ad}(h,t)}{dt} = \rho_z(1-\varepsilon_z)\Delta H_{ads} r_{ads}(h,t) - U_z S_{A,z}((T_{z,ad}(h,t) - T_{a,ad}(h,t))) \quad (8)$$

Air:

$$\rho_a cp_{a,ad}\varepsilon_z \frac{dT_{a,ad}(h,t)}{dt} = -\frac{F_{a,ad}cp_{a,ad}}{A_{ad}}\frac{dT_{a,ad}(h,t)}{dh} + U_z S_{A,z}(T_{z,ad}(h,t) - T_{a,ad}(h,t)) - \frac{4U_{bed,col}}{ID_{col}}(T_{a,ad}(h,t) - T_{amb}) \quad (9)$$

Regenerator

Mass balance of water

Zeolite: $$\frac{dq_{w,reg}(h,t)}{dt} = r_{des}(h,t) \quad (10)$$

Air: $$\varepsilon_z \frac{dq_{v,reg}(h,t)}{dt} = -(\frac{F_{a,reg}}{\rho_a A_{col}})\frac{dq_{v,reg}(h,t)}{dh} - \frac{\rho_z}{\rho_a}(1-\varepsilon_z)r_{des}(h,t) \quad (11)$$

Heat balance

Zeolite: $$\rho_z cp_{z,reg}(1-\varepsilon_z)\frac{dT_{z,reg}(h,t)}{dt} = \rho_z(1-\varepsilon_z)\Delta H_{des} r_{des}(h,t) - U_z S_{A,z}((T_{z,reg}(h,t) - T_{a,reg}(h,t))) \quad (12)$$

Air:

$$\rho_a cp_{a,reg}\varepsilon_z \frac{dT_{a,reg}(h,t)}{dt} = -\frac{F_{a,reg}cp_{a,reg}}{A_{col}}\frac{dT_{a,reg}(h,t)}{dh} + U_z S_{A,z}(T_{z,reg}(h,t) - T_{a,reg}(h,t))..$$

$$.. - \frac{4U_{bed,col}}{ID_{col}}(T_{a,reg}(h,t) - T_{amb}) \quad (13)$$

Dryer

Mass balance of water

product: $$\frac{dq_{w,d}(h,t)}{dt} = -r_{dry}(h,t) \quad (14)$$

Air: $$\varepsilon_p \frac{dq_{v,d}(h,t)}{dt} = -(\frac{F_{a,d}}{\rho_a A_d})\frac{dq_{v,d}(h,t)}{dh} - \frac{\rho_p}{\rho_a}(1-\varepsilon_p)r_{dry}(h,t) \quad (15)$$

Heat balance

Product: $$\rho_p cp_{p,d}(1-\varepsilon_p)\frac{dT_{p,d}(h,t)}{dt} = \rho_p(1-\varepsilon_p)\Delta H_v r_{dry}(h,t) - U_p S_{A,p}((T_{p,d}(h,t) - T_{a,d}(h,t))) \quad (16)$$

Air: $$\rho_a cp_{a,d}\varepsilon_p \frac{dT_{a,d}(h,t)}{dt} = -\frac{F_{a,d}cp_{a,d}}{A_d}\frac{dT_{a,d}(h,t)}{dh} + U_p S_{A,p}(T_{p,d}(h,t) - T_{a,d}(h,t)) - \frac{U_{bed,d}}{l_d}(T_{a,d}(h,t) - T_{amb}) \quad (17)$$

Table 6.2: Additional equations relating to equations 6 to 17

Adsorber	$r_{ads}(h,t)=k_{ads}(q_{e,ad}(h,t)-q_{w,ad}(h,t))$ $k_{ads}=C_1(T_{z,ad}(h,t)+273.15)$ $q_{e,ad}(h,t)=C_2\left[tanh\left(log_{10}(P_{v,ad}(h,t))+C_3T_{z,ad}(h,t)\right)+1\right]$ $C_2=0.1132\,;C_3=-0.0266$ The equilibrium moisture loaded in zeolite is a function of vapor partial pressure and temperature derived from zeolites properties in CECA data sheet[15]. $P_{v,ad}(h,t)=\dfrac{y_{v,ad}(h,t)}{1+y_{v,ad}(h,t)}P_{total}\,;\; y^i_{v,ad}=\dfrac{q_{v,ad}(h,t)/0.622}{1+q_{v,ad}(h,t)/0.622}$ $A_{col}=\dfrac{\pi}{4}(ID_{col})^2\,;S_{A,z}=S_{pa,z}\rho_z\,;\;F_{a,ad}=\dfrac{G_{a,ad}}{1+q_{v,amb}}\,;G_{a,ad}=F_1A_{col}\rho_a$ F_1 is linear velocity of air entering adsorber measured from F1 $cp_{z,ad}=cp_z+cp_wq_{w,ad}(h,t)\,;\;cp_{a,ad}=cp_a+cp_vq_{v,ad}(h,t)$
Regenerator	$r_{des}=k_{des}(q_{e,reg}(h,t)-q_{w,reg}(h,t))$ $k_{des}=C_4(T_{z,reg}(h,t)+273.15)$ $\Delta H_{des}=\Delta H_{ads}$ $cp_{z,reg}=cp_z+cp_wq_{w,reg}(h,t)\,;cp_{a,reg}=cp_a+cp_vq_{v,reg}(h,t)\,;$ $F_{a,reg}=\dfrac{G_{a,reg}}{1+q_{v,amb}}\,;\;G_{a,reg}=F_2A_{col}\rho_a$ F_2 is linear velocity of air entering regenerator measured from F2
Dryer	$r_{dry}=-k_{d0}$ $cp_{p,d}=cp_p+cp_wq_{w,d}(h,t)\,;\;cp_{a,d}=cp_a+cp_vq_{v,p}(h,t)$ $F_{a,d}=F_{a,ad}$ $A_d=w_dl_d\,;V_d=w_dl_dh_d\,;\;S_{A,p}=S_{pa,p}\rho_pw_dl_dh_d$

4. Model validation

4.1. Parameter estimation

Equations 6 to 17 with the additional equations depicted in Table 6.2 were solved using the boundary and the initial conditions as given in Table A-1 (Appendix 6), and using the equipment dimensions, material properties, and the process constants as given in Table A-2 (Appendix 6).

The measured values of the flows and inlet temperatures during operational time were used as input data for the model. The model responses in time were fitted to the experimental measured values of temperature and humidity of the air leaving the adsorber, temperature of air leaving the regenerator, and temperature and humidity of air leaving the dryer. For response fitting and parameter estimation Matlabs' function *fmincon* is used.

The model equations 1-17 contain several physical and kinetic constants which are known from handbooks or product data sheets. The unknown parameters in the set of equations are *C1, C4* (adsorption and desorption rate constants), $U_{bed,col}$ and $U_{bed,d}$ (overall heat transfer coefficients for heat exchange between the columns/dryer and the environment), and k_{d0} (drying rate constant). The estimation of these parameters could partly be separated; i.e. parameters for the adsorber, for the regenerator and for the dryer. The procedure followed the next steps:

1. C_1 was obtained by minimization the sum of squared error (SSE) of humidity of air leaving the adsorber

   $$SSE_{ad} = \sum_{t=t0}^{t=tf}((q_{v,ad}^{experiment} - q_{v,ad}^{model})^2 \qquad (18)$$

   $q_{v,ad}^{experiment}$ was obtained from the relative humidity and temperature of sensor T-RH2 and $q_{v,ad}^{model}$ from equation 7
2. $U_{bed,col}$ was obtained by minimization of the sum of squared error (SSE) of temperature of air leaving the adsorber

   $$SSE_{ad} = \sum_{t=t0}^{t=tf}((T_{a,ad}^{experiment} - T_{a,ad}^{model})^2 \qquad (19)$$

   $T_{a,ad}^{experiment}$ was obtained from the temperature sensors T-H3 or T-H5 depending on the shift and $T_{a,ad}^{model}$ from equation 9. This value of $U_{bed,col}$ was also used for the regeneration.
3. C_4 was obtained by minimization of the sum of squared error (SSE) of the temperature of air leaving the regenerator (analog to equation 19)
4. k_{d0} followed from minimization of the sum of squared error (SSE) of humidity of air leaving the dryer (analog to equation 18)
5. $U_{bed,d}$ followed from the minimization of sum of squared error (SSE) of temperature of air leaving the dryer (analog to equation 19)

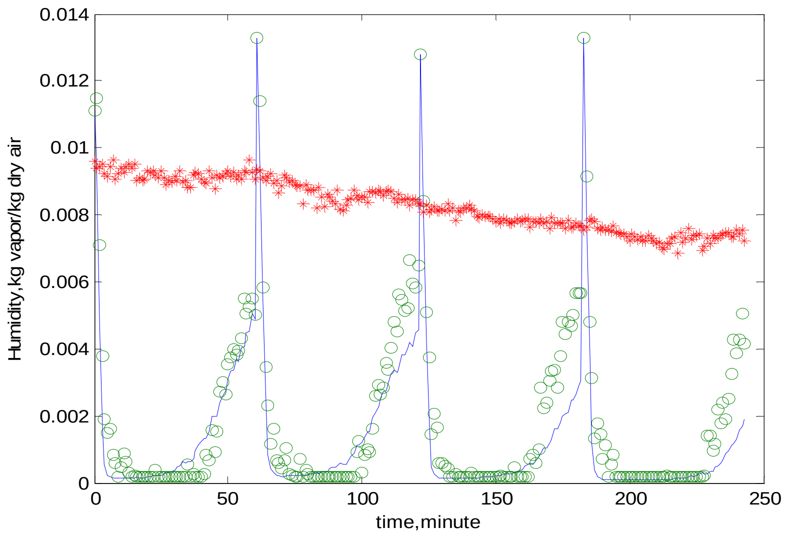
Estimated parameter values are given in Table 6.3, as follows:

Table 6.3: Estimated parameters

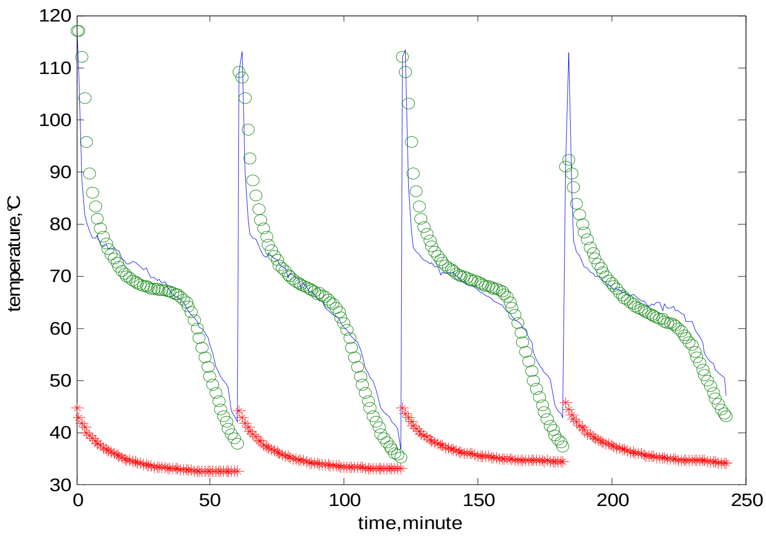
Parameter	Dimension	Estimated values
C_1 ; C_4	1/minute K	0.2×10^{-3}; 0.12×10^{-3}
$U_{bed,col}$ $U_{bed,d}$	kJ/m^2 min°C	1.250; 0.2×10^{-2}
k_{d0}	1/minute	0.14×10^{-2}

4.2. Profile of water content and temperature of air, zeolite and product

Figure 6.3 to 6.5 present the measurements and model results for a shift time of 60 minutes over 4 shift periods. It appeared that the sensors had a first order response with a time constant of approximately 2 minutes. This behavior was mimicked by passing the model outcome through a first order process prior to plotting. Figure 6.3 gives the measurements for the air at inlet (*) and outlet (o) of the adsorber. For every shift, during 2-5 minutes the moist air which is left after regeneration is moved from the adsorber. Then the adsorber reduces the water content in the air by more than 90% for a period of 40 minutes (see Figure 6.3a). After this period, the water uptake capacity of the zeolite in adsorber decreases as the zeolite approaches saturation, and as a result, the humidity of air at outlet of the adsorber increases.



a.



b.

Figure 6.3: Conditions of air entering (*) and exiting the adsorber (° experiment, – model). a: recorded humidity (for a model, at initial time the driving force for adsorption is high due to air contacting with dry zeolite layer). b: recorded temperature

After regeneration the piping towards the column, the column material and the zeolite in the column are hot. As a consequence the inlet temperature starts at 45°C and temperature at the outlet of the adsorber around 110-120°C (see Figure 6.3 part b), i.e. the temperature of the zeolite after regeneration. In the first minutes of a shift, the zeolite is cooled. Subsequently, the temperature remains on a level of 60-70°C due to the release of adsorption heat. Towards the end of a shift the temperature falls because the zeolite becomes saturated and thus the release of adsorption heat goes down. Finally, the air temperature at the outlet of the adsorber is close to the adsorber inlet temperature (*).

The measured data was fitted to the model by estimating the adsorption rate constant (C_1) and the overall heat transfer coefficient between column and environment ($U_{bed,ad}$), see also Table 6.3. Figures 6.3 shows that the humidity and temperature of air leaving the adsorber obtained by the model (-) and experiment (o) are close.

The inlet and exhaust air temperature for the regeneration shift are presented in Figure 6.4. First, it is noted that the inlet temperature of the regenerator (*) starts at about 110°C and increases gradually to 140°C; i.e. the temperature after the heater. This typical response is result of heating-up pipe walls and metal valves between the electrical heater and the entrance of the regenerator. The heat capacity of these components is considerable compared to the heat content of the air flow.

Next, the experimental results show that in the initial 1-2 minutes the regenerator exhaust temperature increases slightly from the temperature which was achieved at the end of the adsorption shift. This effect is result of an initial heating-up. Between 2-10 minutes, the energy is used to release water from the zeolite. Thus, in this period the temperature at the outlet of the regenerator hardly changes. After this period of about 10 minutes less water is removed from the zeolite and as a result the temperature difference between in and outlet of the regenerator becomes smaller. At the end of the shift there is still a temperature difference between inlet and outlet as a result of the heat loss which occurs despite the insulation of the columns.

The air temperature at the outlet was fitted to the model by adjustment of the regeneration rate constant (C_4). Model and experimental results are nearly the same. Remark : water removal could be improved by a higher regeneration temperature, but the equipment was limited in its experimental range.

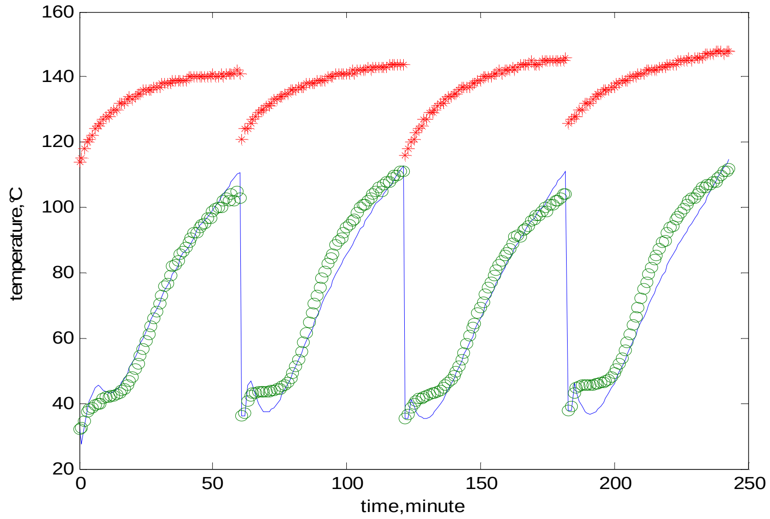


Figure 6.4: Temperature of air: (*) entering and exiting the regenerator (__model, ° experiment)

Figure 6.5 shows the humidity of air at inlet and outlet of the regenerator. The inlet humidity is based on measurements of the ambient humidity, whereas the outlet humidity is reconstructed from the model by using the estimated parameters given in Table 6.3. It was not possible to measure it, because the prevailing high temperature is outside the operating range sensor. The humidity of air leaving the regenerator is for about 2 minutes close to the last value from the adsorber shift. After 2 minutes the humidity increases and the water removal from the zeolite is the highest and later on the water removal decreases during of time. At the end of the shifts the humidity of air exiting the regenerator is close to the inlet humidity (*) which indicates that regeneration is not longer effective.

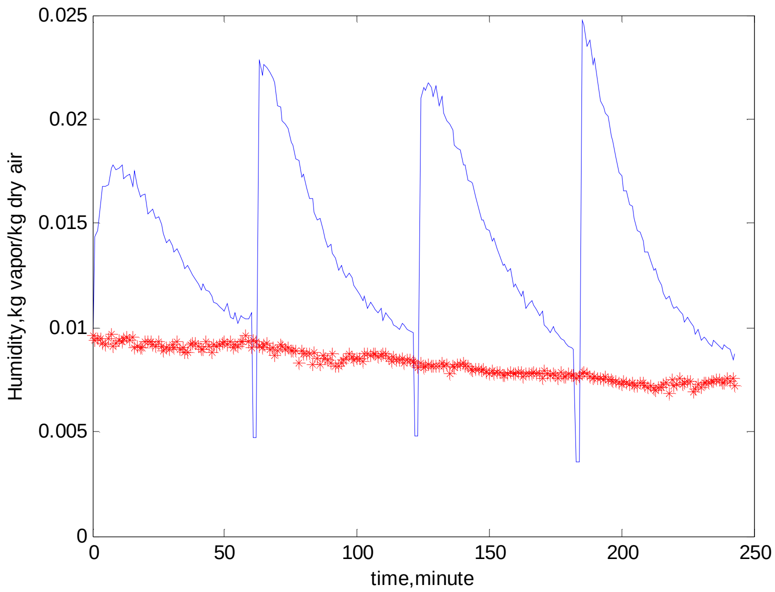
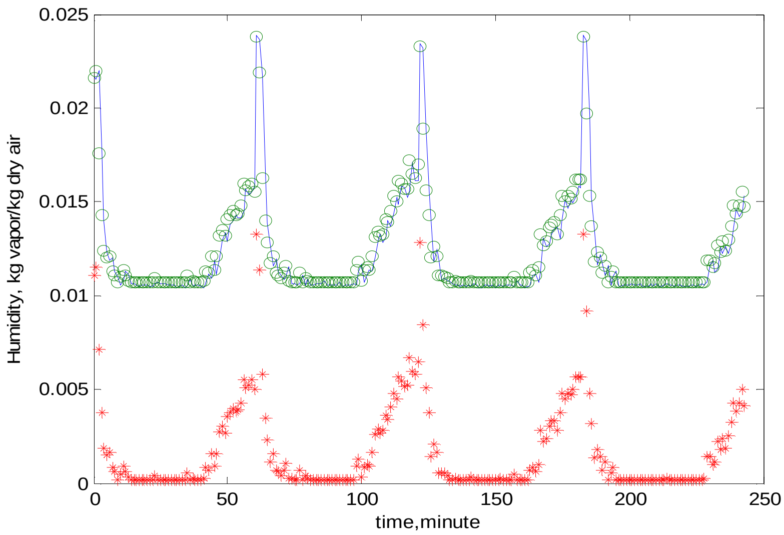
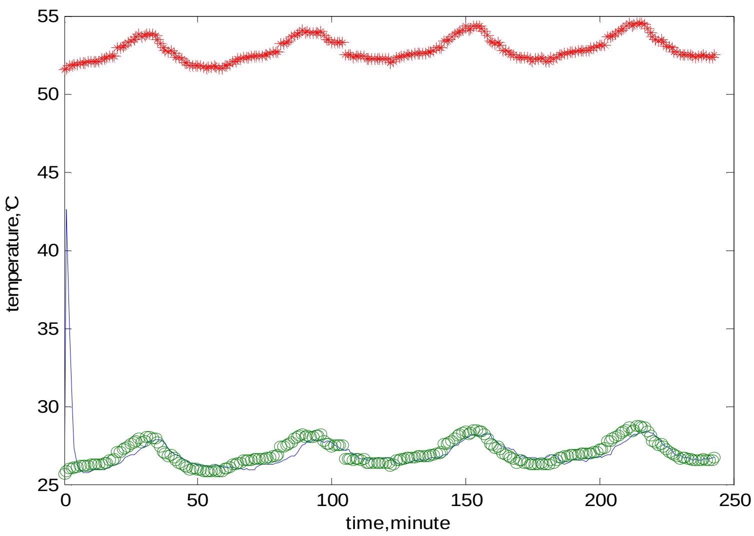


Figure 6.5: Measured humidity of air entering (*) the regenerator and model based reconstruction of humidity at the exhaust of the regenerator (-)

Results for the dryer are illustrated in Figure 6.6. The dehumidified air from the absorber is used as drying medium, but before entering the dryer the air passes the buffer B01, which was not insulated, and the heater HE02 operated at a low constant heating input. The buffer nearly equalizes the temperature and as a result the inlet temperature for the dryer is nearly constant and varies between 52.5-55.0°C (see Figure 6.6 part b).



a.



b.

Figure 6.6: Conditions for air entering (*) and exiting the dryer (° experiment, – model). a: recorded humidity. b: recorded temperature

During these experiments wet product was dried. The vapor pressure of water in the product was high compared to that of the air. As a result, product is dried with a constant drying rate over the whole shift period. The humidity of air at the outlet of the dryer is related to the response of the humidity of air after the adsorber (see Figure 6.6 part a). From the inlet and outlet humidity follows that the drying capacity of air is indeed constant. With the estimated drying rate constant and overall heat transfer coefficient between dryer wall and environment (see Table 6.3) good correspondence between model and experiment is obtained.

4.4. Efficiency calculation

Experimental data of a series of shifts were used to calculate the energy efficiencies according equation 1 to 5. The energy efficiency was also calculated from the fitted dynamic model (equation 6-17) and for the steady state model used in previous work.[4,5] The operational conditions as recorded during the experiments were used as input for the efficiency calculations with the steady state model.

The results in Table 6.5 show that the experimentally obtained heat efficiency is close to that of the model predictions. It is also observed that for a longer shift time the experimentally obtained results come closer to the results of the models.

Table 6.5: Efficiency of the adsorption dryer system at flow of air dryer 1.70 kg/minute and air regenerator 1.90 kg/minute

Shift Time, min	Efficiency , (%)		
	Experimental	Dynamic Model	Steady state model
30	50.4	49.7	53.2
45	52.7	51.6	53.9
60	53.9	52.8	54.8

5. Sensitivity Analysis

The experiments were done for a range of conditions that could be realized with the experimental installation. As the model is based on laws of conservation it allows to extrapolate to other operational conditions and so the model is used to investigate the effect of drying conditions on the energy efficiency.

5.1. Effect air flow ratio and shift time

The experimental installation functions the best for a 1:1 ratio between the air flow for adsorption/drying and air flow for regeneration. With higher flow rates fluidization and entrainment of the particles occurred. Figure 6.7 shows that the energy efficiency increases if the ratio between the air flow for drying and air flow for regeneration increases. At a ratio 3.5-4.0:1 the efficiency is 70-72% which is similar to the calculations results in the previous study using a steady-state model and a flow ratio 4:1[4,5]. This ratio is result of the fact that hot air used for water removal from zeolite at 110-140°C can contain about 4 times more water than moderately heated air for water removal from the product at 50°C. So, a lower air flow suffices for regeneration, and hence heat input is less.

The shift time also affects the energy efficiency and the best performance is obtained for a shift time of 60 minutes. Main reason is that for a short shift time (for example 30 minutes) the zeolite is not sufficiently regenerated, which lowers the efficiency of the zeolite for air dehumidification over a series of shifts.

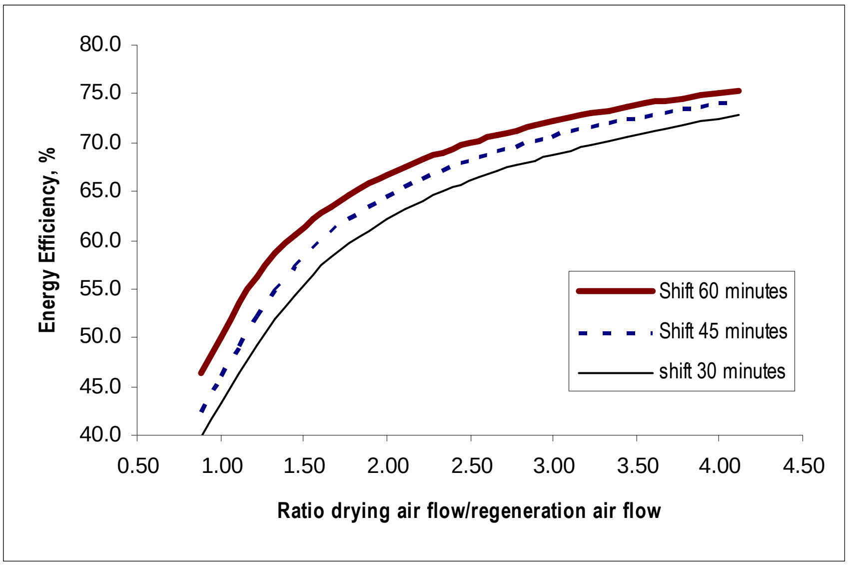


Figure 6.7: Effect of ratio drying air flow/regeneration air flow. Shift times 30, 45, 60 minutes, ambient temperature 20°C, RH 40%

5. 2. Properties of ambient air used for drying

At a higher moisture content in the inlet air, the time until the zeolite becomes saturated is shorter, but the total amount of released heat remains the same. As a consequence, the relative humidity of ambient air used for drying has not much effect on the energy efficiency (see Figure 6.8).

The temperature of the ambient air used for drying affects the energy efficiency significantly (see Figure 6.9); a higher ambient air temperature is beneficial:

– A higher ambient temperature yields an almost equally higher temperature of air from the adsorber. Hence, the required energy to heat the dehumidified air to the dryer temperature decreases.

– In a similar way the energy to heat ambient air to the regeneration temperature is lower. Moreover, there is some advantage from the higher temperature of the spent zeolite at the end of the adsorption shift which requires less energy to achieve the regeneration temperature.

– Heat loss from air in the equipment to the environment is lower.

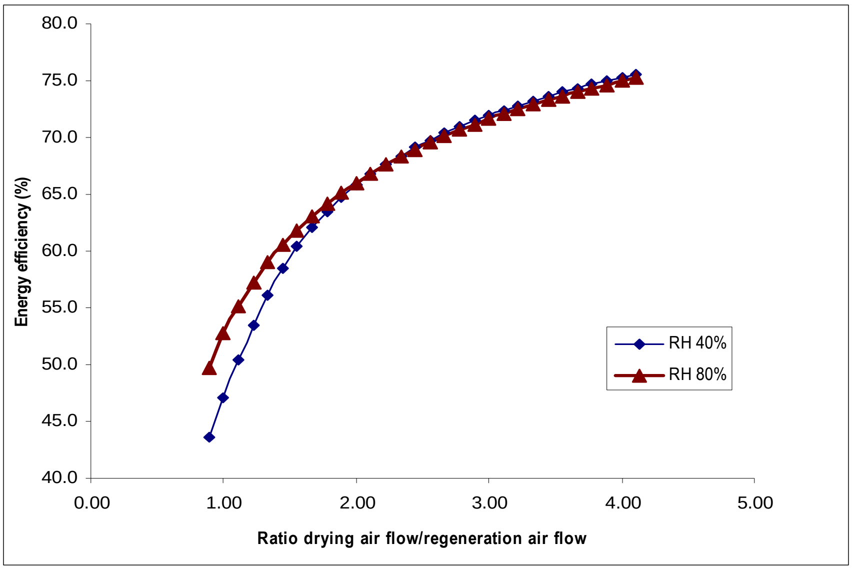


Figure 6.8: Effect of ratio drying air flow/regeneration air flow. Shift time 45 minutes, RH 40%,80% and ambient temperature 20°C

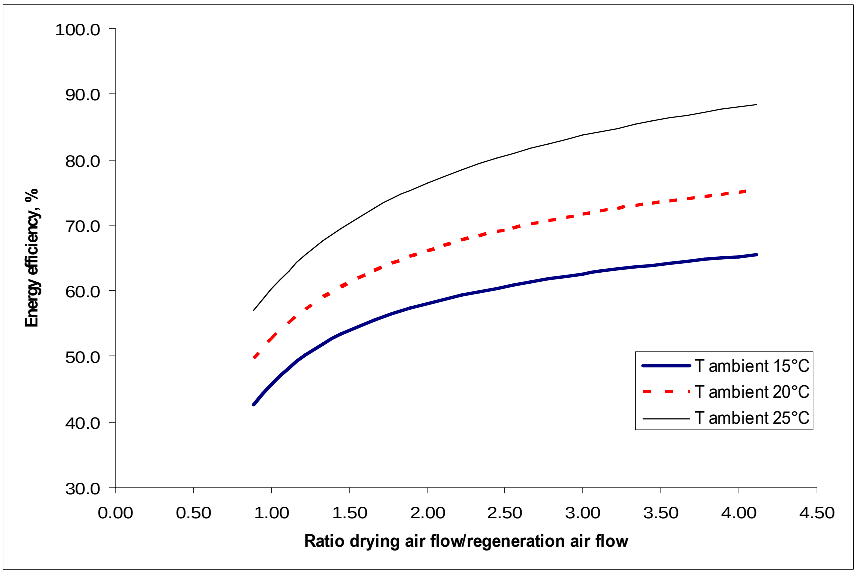


Figure 6.9: Effect of ratio drying air flow/regeneration air flow. Shift time 45 minutes, RH 40% and varying ambient temperature at 15, 20 and 25°C.

5. Conclusion

In previous work[5] adsorption drying with zeolites and their potential to improve the energy efficiency in drying have been discussed. In this work the energy efficiency of a single-stage system is experimentally evaluated in a twin-column system with zeolite as adsorbent. The twin-columns are alternately used for air dehumidification and for zeolite regeneration.

The experimental results yielded energy efficiencies in the range 50-55%. Application of the experimental conditions to the steady-state model used in the previous study resulted in energy efficiencies values which correspond to the obtained experimental results. So, the steady state model gives reliable predictions of the energy efficiency which can be realized.

To be able to extrapolate the experimental results to other operational conditions the experimental results were fitted to a dynamic model of the twin-column system. A sensitivity study for the main process variables on this model indicated that the ratio between air flow used for drying and air flow used for regeneration affects the energy efficiency significantly. If this ratio is 4:1, (as applied in previous study) an energy efficiency of 70-75% is obtained, which corresponds to the result of previous work. Other important variables that affect the efficiency are the temperature of air used for drying and the shift time.

The experimental work confirms that predictions made with the model in previous work are accurate. The work confirms also the predicted potential of using zeolite for air dehumidification in drying.

Acknowledgement

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Appendix 6

Table A-1: Boundary condition and initial condition

Adsorber	parameter	Position (*h*)	Boundary condition	Initial condition See Table A-1, appendix
	$q_{v,ad}$ $T_{a,ad}$ $q_{w,ad}$; $T_{z,ad}$	0	$q_{v,ad}(0,t)=q_{v,amb}$; $T_{a,ad}(0,t)=T_{amb}$ $\frac{dq_{w,ad}(0,t)}{dt}$; $\frac{dT_{z,ad}(0,t)}{dt}$ *(analog eq.6 & 8)*	$q_{v,ad}(h,0)=q_{v,reg}(h,t_c)$ $q_{w,ad}(h,0)=q_{w,reg}(h,t_c)$
	$q_{v,ad}$ $T_{a,ad}$ $q_{w,ad}$ $T_{z,ad}$	h_{ad}	$\frac{dq_{v,ad}(h_{ad},t)}{dt}$; $\frac{dT_{a,ad}(h_{ad},t)}{dt}$ *(analog eq. 7&9)* $\frac{dq_{w,ad}(h_{ad},t)}{dt}$; $\frac{dT_{z,ad}(h_{ad},t)}{dh}$ *(analog eq. 6&8)* $T^{out}_{a,ad}=T_{a,ad}(h_{ad},t)$; $q^{out}_{v,ad}=q_{v,ad}(h_{ad},t)$	$T_{a,ad}(h,0)=T_{a,reg}(h,t_c)$ $T_{z,ad}(h,0)=T_{z,reg}(h,t_c)$
Regenerator	$q_{v,reg}$ $T_{a,reg}$ $q_{w,reg}$ $T_{z,reg}$	0	$q_{v,reg}(0,t)=q_{v,amb}$; $T_{a,reg}(0,t)=T^{in}_{a,reg}$ $\frac{dq_{w,reg}(0,t)}{dt}$; $\frac{dT_{z,reg}(0,t)}{dt}$ *(analog eq. 10 & 12)*	$q_{v,reg}(h,0)=q_{v,ad}(h,t_c)$ $q_{w,reg}(h,0)=q_{w,ad}(h,t_c)$
	$q_{v,reg}$ $T_{a,reg}$ $q_{w,reg}$ $T_{z,reg}$	h_{reg}	$\frac{dq_{v,reg}(h_{reg},t)}{dt}$; $\frac{dT_{a,reg}(h_{reg},t)}{dh}$ *(analog eq. 11&13)* $\frac{dq_{w,reg}(h_{reg},t)}{dt}$; $\frac{dT_{z,reg}(h_{reg},t)}{dt}$ *(analog equation 12)* $T^{out}_{a,reg}=T_{a,reg}(h_{reg},t)$; $q^{out}_{v,reg}=q_{v,reg}(h_{reg},t)$	$T_{a,reg}(h,0)=T_{a,ad}(h,t_c)$ $T_{z,reg}(h,0)=T_{z,ad}(h,t_c)$
Dryer	$q_{v,d}$; $T_{a,d}$ $q_{w,d}$; $T_{p,d}$	0	$q_{v,d}(0,t)=q_{v,ad}(h_{ad},t)$; $T_{a,d}(0,t)=T^{in}_{a,d}$ $\frac{dq_{w,d}(0,t)}{dt}$; $\frac{dT_{p,d}(0,t)}{dt}$ *(analog eq. 14 &16)*	$q_{v,d}(h,0)=q_{v,ad}(h_{ad},t_c)$ $q_{w,d}(h,0)=q^{0}_{w,d}$
	$q_{v,d}$; $T_{a,d}$ $q_{w,d}$; $T_{p,d}$	h_d	$\frac{dq_{v,d}(h_d,t)}{dh}$; $\frac{dT_{a,d}(h_d,t)}{dt}$ *(analog eq. 15& 17)* $\frac{dq_{w,d}(h_d,t)}{dt}$; $\frac{dT_{p,d}(h_d,t)}{dt}$ *(analog eq. 14& 16)* $T^{out}_{a,d}=T_{a,d}(h_d,t)$; $q^{out}_{v,d}=q_{v,d}(h_d,t)$	$T_{a,d}(h,0)=T^{0}_{a,d}$ $T_{p,d}(h,0)=T^{0}_{p,d}$

Table A-2: Material properties and equipment data

Notation	Parameter		Value
$h_{ad}\,;ID_{col}$	Height and inside diameter of adsorber, m		0.24;0.15
ID_{pipe}	inside diameter of pipe, m		0.05
$w_d\,;l_d\,;h_d$	Width, length and height of dryer, m		0.3;0.3;0.4
	Weight of zeolite used (gram)		2500
$S_{pa,z}\,;S_{pa,p}$	Specific surface area of zeolite) and product (m^2/g)[16]		20; 20
t	Time, minute		
$\varepsilon_z\,;\varepsilon_p$	Porosity of zeolite and product in bed		0.3;0.4
ρ_z	Density of zeolite (kg/m^3)[16]		736.5
ρ_p	Density of product (kg/m^3)		36
ρ_a	Density of air (kg/m^3)		1.08
$U_z\,;U_p$	Overall heat transfer coefficient of zeolite[17] ; product, $kJ/m^2min°C$		0.116
ΔH_{ads}	Latent heat of water adsorption (kJ/kg)[15]		4400
cp_v	Specific heat of vapor (kJ/kg ^oC)		1.93
cp_a	Specific heat of dry air (kJ/kg ^oC)		1
cp_w	Specific heat of water (kJ/kg ^oC)		4.2
cp_p	Specific heat of dry product (kJ/kg ^oC)[16]		0.920
ΔH_v	Latent heat of water evaporation (kJ/kg)		2500
$G_{air,ad}$	Flow rate of air for adsorber or dryer, kg/h		1.70
$G_{air,reg}$	Flow rate of air for regenerator, kg/h		2.00
T_{amb}	Ambient temperature (measured), °C		17-20
RH_{amb}	Ambient relative humidity (measured), %		35
$q_{v,amb}$	Humidity of ambient air		0.0065-0.0090
$T_{a,reg}$	Temperature of inlet regenerator		110-130
$T^{in}_{a,d}$	Temperature of inlet dryer		50
	Initial condition for shift 1 (first shift)		
$q_{w,ad}(h,0)$	Adsorber	Water in zeolite, kg water/kg dry zeolite	0.025
$T_{z,ad}(h,0)$		Temperature of zeolite, °C	40
$q_{v,ad}(h,0)$		Humidity of air, kg vapor/kg dry air	0.008
$T_{a,ad}(h,0)$		Temperature of air, °C	40
$q_{w,ad}(h,0)$	Regenerator	Water in zeolite, kg water/kg dry zeolite	0.16
$T_{z,reg}(h,0)$		Temperature of zeolite, °C	80
$q_{v,reg}(h,0)$		Humidity of air, kg vapor/kg dry air	0.008
$T_{a,reg}(h,0)$		Temperature of air, °C	120
$q_{w,d}(h,0)$	Dryer	Water content in product, kg water/kg dry product	10
$T_{p,d}(h,0)$		Temperature of product, °C	18
$q_{v,d}(h,0)$		Humidity of air, kg vapor/kg dry air	0.001
$T_{a,d}(h,0)$		Temperature of air, °C	50

Chapter 7

Adsorption Drying with Zeolite:

Evaluation and Future Development

1. Research achievements and evaluation

The drawback of low and medium temperature drying in processing food products and other heat sensitive products is the high energy consumption. The energy efficiencies are in the range of 25-60%, which means that to remove one kilogram of water from a product the energy equivalent of 1.6-4.0 kg of steam is required. With the current drastic increasing prices for fossil fuels, the operational costs for drying increase along a corresponding trend. Due to the world wide increasing demand for energy it is expected that in the future the increase of operational cost for drying process will continue.

This situation makes the development of efficient drying methods for high quality heat sensitive products more and more important, and raises a challenge for research in drying technology. However, during the last decades, innovation and research in drying technology tended to reach a saturation level and a further significant reduction in energy consumption seemed not feasible. Nevertheless, positive results were obtained in zeolite drying to improve energy efficiency for low and medium temperature operations which are suitable for retaining high quality of heat sensitive products. My research questions are:

1. How to use zeolite to enhance the energy efficiency of drying systems,
2. How to recover heat flows in dryer-adsorption-regeneration system,
3. What is the potential for a multistage zeolite drying system?
4. How to design the zeolite drying process operation with proper dimension of equipment
5. Can the zeolite drying system be validated?
6. How to use the obtained knowledge to design an energy effective dryer

The principle of this research is directed on the improvement of the driving force in the dryer by reducing the humidity of air through an adsorption system using zeolite before entering the dryer. In this way, at least two advantages can be obtained:

1. the air humidity of the drying air is made low (more than 99% can be removed) which increases the capacity of air for taking up water from the product and speeds-up the drying,
2. the air temperature increases due to the adsorption heat released during vapor removal which reduces the heat demand for drying.

These advantages result in an energy efficient drying system. However, after taking the required energy for regeneration of the spent zeolite into account, the overall energy efficiency improvement is still marginal. Moreover, zeolite regeneration requires high temperatures which increase the costs for hot utility.

To enhance the overall energy efficiency, heat is recovered with a heat exchanger network designed on the principles of pinch technology and which is integrated with the zeolite dryer for recovering heat in the hot exhaust air from the regenerator. The hot air is reused to heat the air which is fed to the regenerator, and the remaining heat is used to heat the dehumidified air for drying. This method reduces the total heat that has to be supplied by a hot utility unit and increases the energy efficiency of the zeolite dryer system as well. The energy efficiency of a single-stage zeolite dryer with 2-4 heat exchangers for heat recovery operating in the range of 60-90°C is 70-75% which is 10-15% higher than that of a conventional dryer operating under comparable conditions.

Multistage zeolite drying has potential for further improvement of the energy efficiency. In such system product is dried in a number of succeeding stages. The product in the first stage is dried with air dehumidified by zeolite. After passing an adsorber bed with zeolite, the exhaust air from this stage is reused for product drying in a next stage. This concept is repeated several times. The system can be operated as a co-current, counter-current or cross-current system. The main benefit of the system is that the energy content of the exhaust air is reused several times. Moreover, the released adsorption heat is utilized for drying in the succeeding stages. As a consequence, product drying hardly requires heat supply. The required heat for the regeneration of zeolite is kept low by pinch technology based heat recovery.

Multistage zeolite drying systems with 2,3 or 4 stages have been configured and evaluated in combination with a heat exchanger network for heat recovery. Calculation results obtained from a steady-state model based on overall mass and heat balances, showed that the energy efficiency of a multistage system is significantly higher than that of conventional drying systems and single-stage zeolite drying systems. The efficiency increases with the number of stages, but a multistage system with 3 stages seems most effective. Above this number the energy efficiency improvement is marginal and probably not sufficient to justify the increase of system complexity. The counter-current dryer is most efficient and achieves an energy efficiency of 88% for a 3-stage system. However, the heat recovery unit did not work effectively, since it recovers only 16-20% of the total heat in the exhaust air.

To increase the effectiveness of the heat recovery the pressure of the hot exhaust air from the regenerator is increased by using a compressor. As a result the temperature and dew point of the air increase. Now, the system recovers more sensible heat and also latent heat from vapor condensation. After taking into account the energy required for air compression, the benefits were canceled. The other way is to use the compressed air to heat up other cold streams. In this work air for an additional drying stage is heated. It brings the energy efficiency to 110-120% which implies that the energy consumption can be halved.

The focus in this work was on operational temperatures for drying in the range 60-90°C. Besides this range the performance of the multistage zeolite dryer system was also evaluated for operational dryer temperatures in the range 10-50°C. The dryer was compared with a conventional drying system which uses dehumidified air obtained by condensation and in both systems a heat recovery was applied. The energy efficiency of the multistage zeolite dryer system is superior to the condensation system for ambient air temperatures in the range 10-25°C and relative humidity in the range 50-80%. Results showed that the energy efficiency of three-stage zeolite dryer is 15-50% higher than that of a conventional condenser dryer.

To take the next step ahead towards the specification of the dryer characteristics and dimensions and to integrate the drying and adsorption/desorption process, computational fluid dynamic (CFD) calculations were performed for a combined adsorber-dryer-regenerator system. The two-dimensional CFD model gives the temperature and water content distribution for all units (dryer, adsorber and regenerator) and reveals characteristic phenomena relevant for finding bottlenecks and to improve the design. The CFD calculations are powerful to estimate the dimensions and type of equipment for industrial applications of multistage drying. The results show that the technical realization and operation of a multistage dryer with a continuous moving bed of zeolite (CMBZ-dryer) is feasible. Moreover, the energy efficiency obtained from the CFD calculations is close to the results obtained from the steady-state model based on overall mass and heat balances.

An experimental installation for a single-stage zeolite dryer has been set up to validate the drying concept. The energy efficiency of the dryer was evaluated and compared to the energy efficiency obtained from the models. By taking into account the heat recovery potential and heat loss to the environment of the experimental installation, the experimental results are close to that obtained with the steady-state model under comparable operational conditions.

It was found that the energy efficiency is most influenced by the ratio between the air flow for drying and the air flow for regeneration of spent zeolite. Other important variables are ambient temperature and the time during which the adsorber/regenerator units are used. Energy efficiencies in the range 50-75% are obtained; the highest values are obtained for a ratio between the air flow for drying and the air flow for regeneration of spent zeolite of 4:1.

Above, the work and achievements on 5 research questions have been discussed. An essential aspect how to use the knowledge for the design of an effective dryer remains. A first, step in that direction is discussed in the next section.

2. Outlook and perspective for realization

2.1. Adsorption dryer development

The results for the calculations for the drying concept using zeolite for air dehumidification and the experimental results are impressive and match each other: it makes further development of the zeolite dryer concept relevant. There are two possible directions for development. The first is using the twin-columns with zeolite working in shift for air dehumidification, the other one is a continuous system with a moving bed of zeolite. Figure 7.1 shows these concepts.

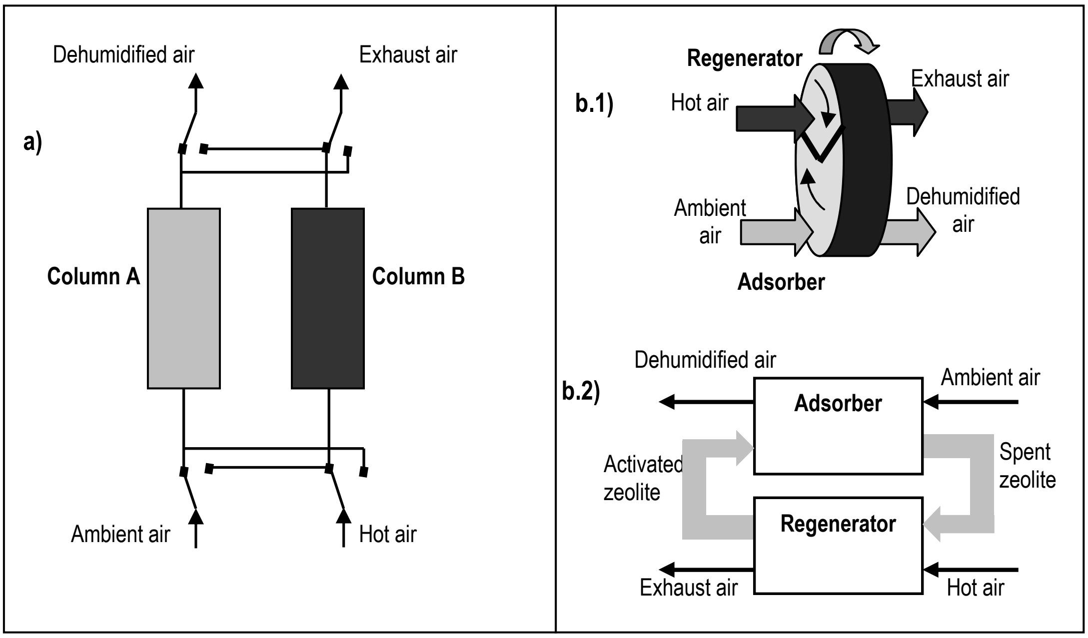

Figure 7.1: A twin-column (part a) versus a two options for a continuous moving bed of zeolite system for air dehumidification: rotating wheel (b.1), and conveying bed of zeolite (b.2)

In the twin column system the columns are alternatingly used as adsorber or regenerator. There are two options to realize the continuous moving bed system. One option is a system were zeolite is mechanically transported by a “pump” or belt system (Figure 7.1 b.2), the other option is a rotating wheel with fixed zeolite particles (Figure 7.1 b.2). By its rotation zeolite passes first the adsorber section, then the regeneration section and returns subsequently to the adorber section.

Figure 7.2 gives the realisation of single-stage systems using the twin column and the continuous moving bed of zeolite. The system with the twin-columns has its complexity in the regulation of the adsorber–regenerator shifts by a periodically adjustment of the valves for the adsorption and regeneration function. Moreover, in this system the dynamic responses for air temperature and humidity after switching the column function may disturb the drying system, and it might be a problem to realize the ratio between air flow for drying and air flow for regeneration of 4:1.

The moving bed adsorbent-regeneration systems are realistic options to substitute the twin column system. In the moving bed system the spent zeolite from the adsorber is continuously fed to the regenerator. At the other side at the exhaust of the regenerator the activated zeolite enters the adsorber. The system can be operated as a single or multistage dryer system. A drawback of this system is that it requires a system for zeolite transport which needs extra attention. The zeolite transport in the wheel construction is relative simple, and the flow ratio 4:1 can be realized easily by using 80% of the wheel surface for adsorption and 20% for regeneration.

In both systems, the temperatures of the air flows are controlled by manipulating the heat flow towards the heaters, and the flow of air is kept at set-point by air flow control. The moisture content in product could be controlled by the temperature of air entering the dryer. However, in practice, the moisture in product is often difficult to measure on-line. In that case either the relative humidity or temperature of air exiting dryer is used to control the moisture in product. These control loopsms are similar to standard controls applied in drying. Thus this system for zeolite drying can be realized with current technology.

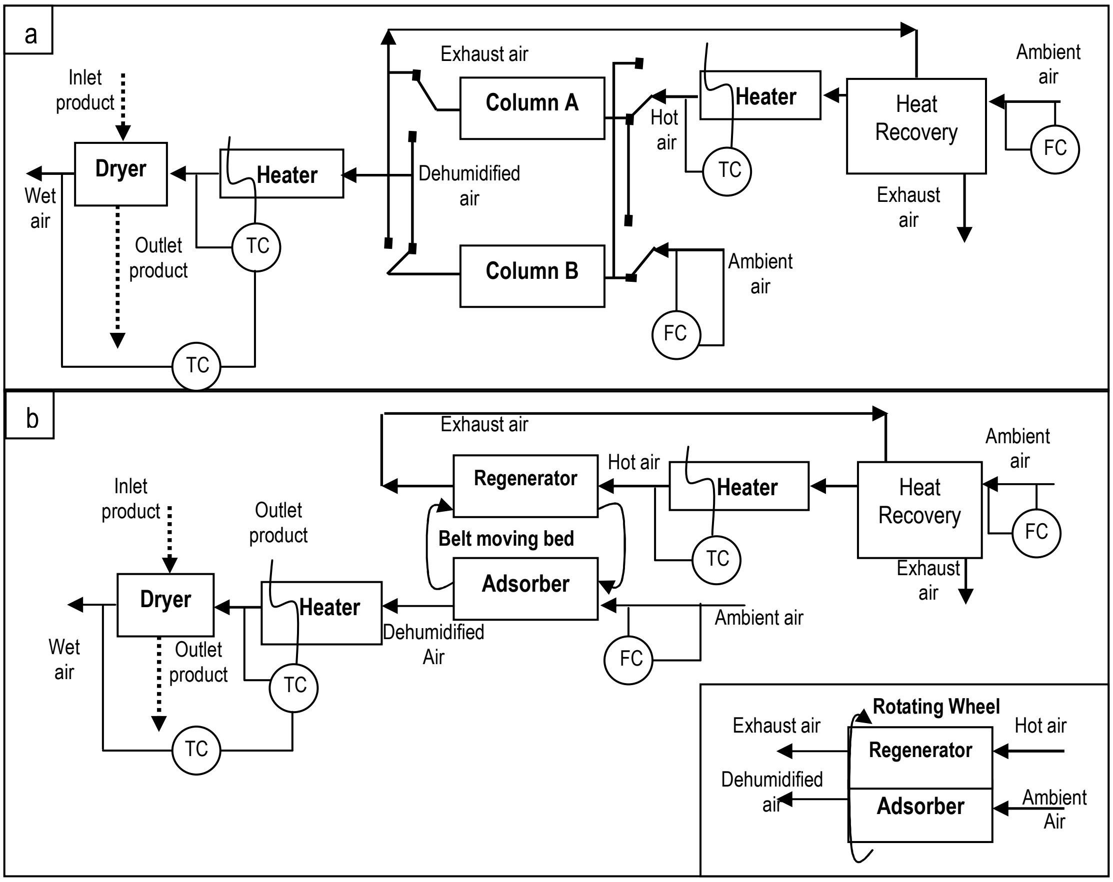

Figure 7.2:a. Single-stage zeolite dryer with fixed bed adsorber-regenerator working in shift; b. Single-stage zeolite dryer with moving bed adsorber-regenerator

Figure 7.3 presents a two-stage dryer systems with adsorber-regenerator working in shift and a continuous moving bed of zeolite dryer. In both systems, the exhaust air from the dryer passes the adsorber in stage 2, while the hot air exiting the first stage regenerator enters the second stage regenerator. The extension to two stages improves the energy efficiency and can be improved further by using 3 or 4 stages. The control loops are similar as for the single-stage system and can be realized with common control systems.

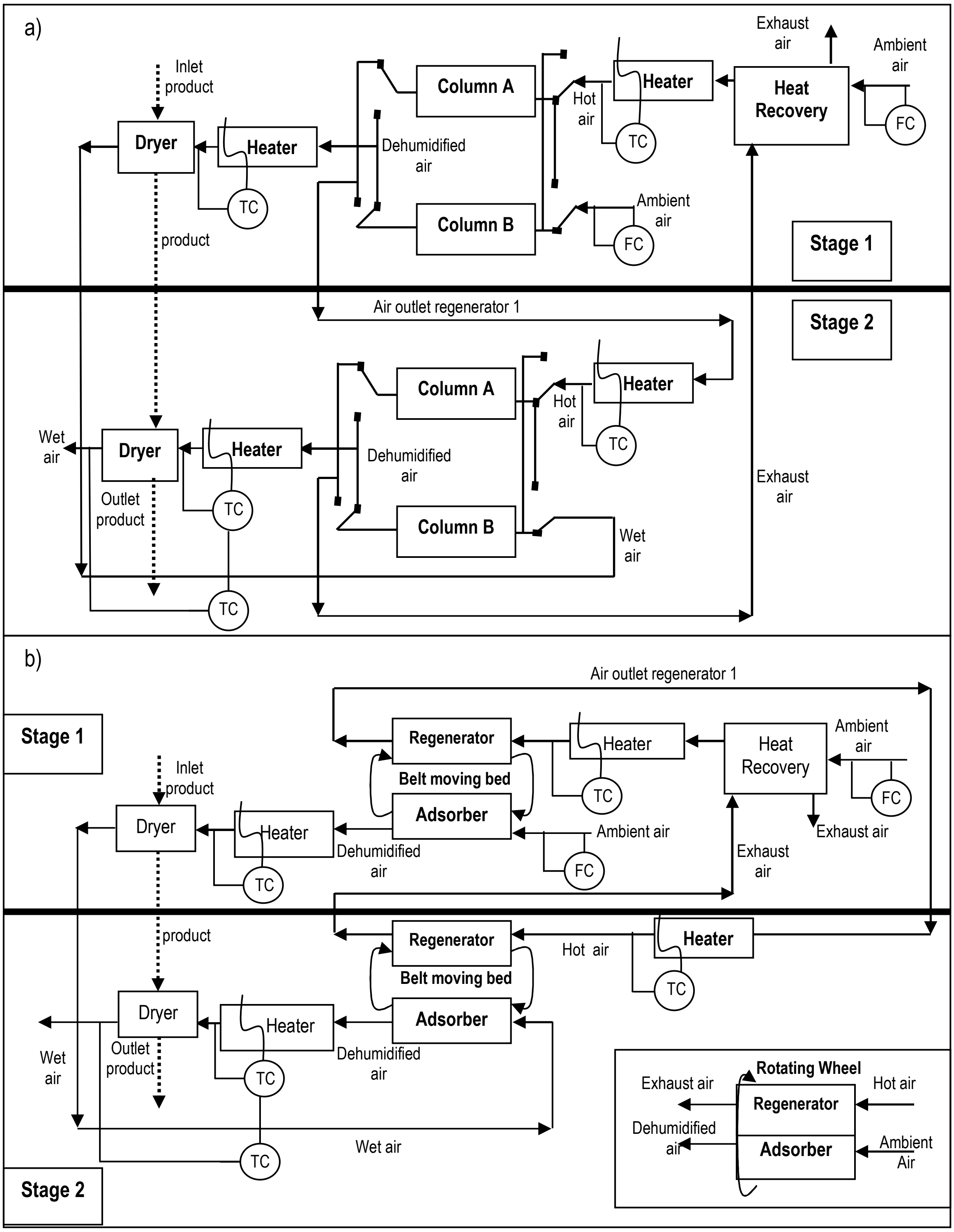

Figure 7.3: a.Two-stage zeolite dryer with fixed bed adsorber-regenerator column working in shift; b.Two-stage zeolite dryer with moving bed adsorber-regenerator

3. Sensitivity analysis

Operational systems based on the twin-colums or continuous moving bed of zeolite may differ in their performance under varying operational conditions. Therefore, both systems are evaluated with respect to the energy efficiency for varying operational variables and process constants. This evaluation is based on the following procedure:

1. Configuring a steady state model for the one and two stage systems for the twin-column system and the continuous moving bed operation (see Figure 7.2 and 7.3).
2. Identifying the controllable and non-controllable inputs and the most important process constants. The operational conditions and process constants from Chapter 6 are used.
3. Specifying the effect of the input variables and main process constant on the energy efficiency for single stage and two stage operation by change of input -20% and +20% from the defined operational conditions.

The results for the sensitivity analysis are given in Table 7.1. As concluded in previous chapters, the energy efficiency for the two-stage system is better than that of the single-stage system. Moreover, for the standard operational conditions the energy efficiencies for the twin-column system and the system with continuous moving bed of zeolite are comparable. For the same stage number, the trend for variations in the input variables and process constants on the energy efficiency are identical. Hence, it can be concluded that there is no specific preference for one of the systems.

From the sensitivity analysis the input variables that affect the energy efficiency are identified. This result is useful to define a strategy to keep the process at the highest performance. The effect of the process parameters is relevant for the construction of the equipment. The results in Table 1 show that the ratio between air flow to the dryer and air flow to the regenerator, and the flow of zeolite (for moving bed) are most important variables to control the energy efficiency of the process. Increasing the air flow to the regenerator decreases energy efficiency, while increasing the air flow for drying and the zeolite flow result in an improved energy efficiency.

The ambient air temperature and product temperature as non-controllable variables affect the performance significantly. Higher ambient and product temperatures reduce the total amount of required energy for heating of air for drying and regeneration, and hence the energy efficiency increases.

The drying rate constant is the process constant which affects the energy efficiency the most. The result is according expectation as with a higher drying rate the dryer operates more efficiently. It must be realized that in this work the dryer is used to evaporate free water at a constant drying rate. The optimal conditions and equipment dimensions for drying products in the falling rate drying period will be different.

The material used for the zeolite bed columns and dryer affect the heat loss and thus the energy efficiency. For the construction of zeolite dryer installations the zeolite column needs a high quality insulation to reduce the heat loss to the environment. The effect of the heat transfer coefficient on the energy efficiency is the strongest for the regeneration part of the installation. Whereas, for a dryer and adsorption system working below 70°C, the effect of the heat transfer coefficient to the environment seems not critical.

Table 7.1: Sensitivity analysis results. Effect of process variables and parameters on energy efficiency for single and two-stage zeolite dryer systems both for a twin-column system and a system with continuous moving bed of zeolite

Observed parameters and variables	**Energy efficiency at basis conditions**			
	1-stage continuous moving bed	**1-stage shift bed**	**2-stage continuous moving bed**	**2-stage shift bed**
Basis capacity and condition based on results of chapter 6	74.0%	72.0%	80.0%	79.5%
Observed parameters and variables	$\frac{\Delta\eta}{\Delta Input}$ (ΔEfficiency % / Δinput change)			
Adjusted variables:				
Air flow for dryer	1.06	1.49	1.53	1.52
Temperature air for dryer	-1.19	-1.18	-1.19	-1.16
Air flow for regeneration	-4.46	-4.78	-2.55	-2.09
Temperature air for regeneration	-0.08	-0.09	-0.11	-0.11
Flow of product	0.01	0.01	0.02	0.02
Flow of zeolite	2.08		4.16	
Un-adjusted input:				
RH of ambient air	0.01	0.01	0.01	0.01
Temperature of ambient air	2.45	2.23	1.36	1.31
Temperature of inlet product	0.00	0.00	0.02	0.02
Water in product	-0.00	-0.01	-0.01	-0.01
Process parameters:	$\frac{\Delta\eta}{\Delta Input}$ (ΔEfficiency(%) / Δinput change(%))			
Ad/desorption rate constant	0.01	0.03	0.02	0.01
Drying rate constant	0.78	0.89	0.49	0.48
Porosity of zeolite	-0.06	-0.06	-0.08	-0.07
Adsorption heat	0.04	0.04	0.05	0.04
Overall heat transfer coefficient from adsorber to environment	0.00	0.00	0.00	0.00
Overall heat transfer coefficient from regenerator to environment	-0.04	-0.04	-0.07	-0.08
Overall heat transfer coefficient from dryer to environment	0.00	0.00	0.00	0.00

4. Options for technical realization

Due to the similar results the system can be operated in several ways in which the zeolite and air have efficient contact and in which the dehumidified air improves the evaporation of water from the products. In the next sections some options for technical realization of multistage zeolite dryer systems are discussed.

a. Continuous moving bed dryer designed in rotating zeolite jacket

The continuous moving bed zeolite can be combined with a rotating zeolite jacket cylinder (see Figure 7.4). The zeolite jacket is divided in a section for adsorption and a section for regeneration. These sections consist of several parts depending on the number of stages. Wet product is fed to the dryer at desired flow, water content and temperature and is transported by the conveyor belt through the dryer. After passing the adsorption section the heated dry air contacts the product for drying. The product goes on to a next section which is separated from the current section by a flexible baffle. The baffle makes that the saturated air is forced to the following adsorption section to be dried and reused at the next step. By the rotation of the cylindrical jacket, the zeolite is transported from the adsorption section to the regeneration section and subsequently to the adsorption section again. The proposed system recovers energy in the exhaust air from the dryer and regenerator.

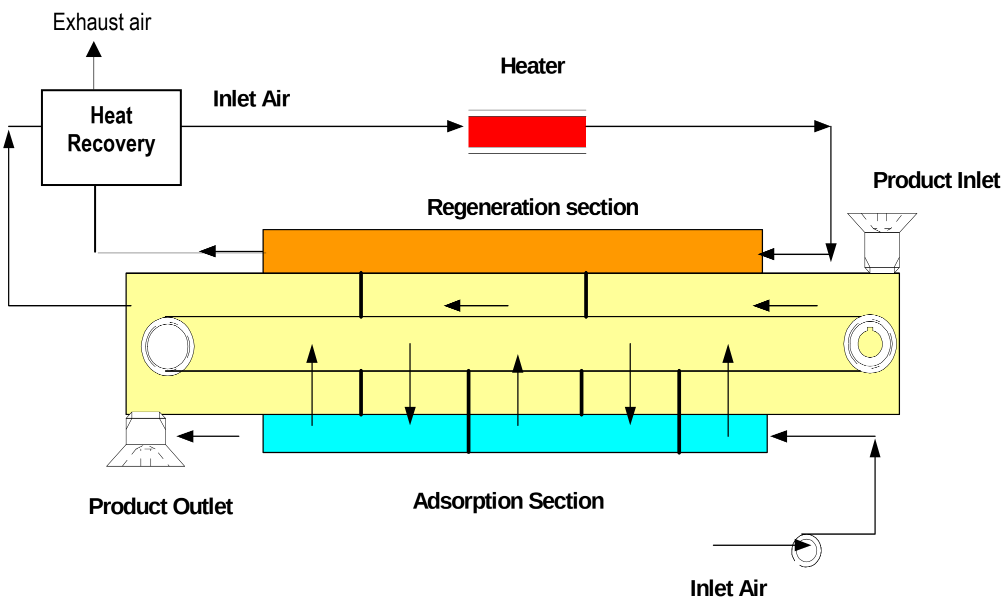

Figure 7.4: Rotating zeolite jacket cylinder with belt dryer

b. Rotary wheel for multistage adsorber

In this system the adsorbent wheel is divided in a number of adsorption sections (depending on the number of stages) and one section for regeneration (see Figure 7.5a). The wheel rotates with a certain angular speed depending on the capacity of air flow. First, the ambient air contacts the zeolite in section 1 of the wheel and passes then the first stage of dryer. The wet air from the first drying stage is dehumidified in section 2 of the wheel and is subsequently used in the second stage of the dryer. This system is repeated. The zeolite comes close to saturation in the last adsorption section of the wheel and then it will be regenerated in the regeneration section by using hot air. The exhaust hot air from the regenerator can be recycled to recover sensible heat.

Furthermore, for obtaining a higher efficiency it is an option to compress the exhaust air from the regenerator (see Figure 7.5b). In this way, the exhaust air from the heat recovery unit has a higher temperature and dew point as well as a higher total pressure. The exhaust air is then contacted with air used as drying medium for an extra dryer in order to recover both sensible and latent heat of vapour condensation. This combination makes the total heat recovery more efficient.

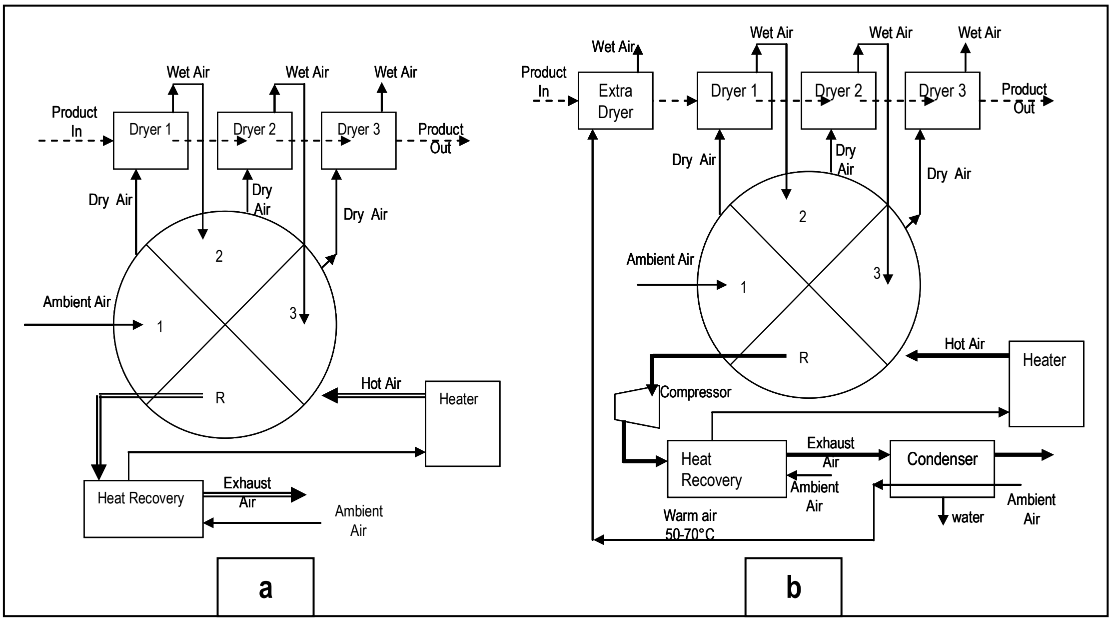

Figure 7.5: Rotary wheel multistage adsorber in combination with compressor and extra dryer (R=Regeneration; 1,2,3..adsorption zone)

c. Fluidized adsorber for the spray and fluidised bed dryer

The principle of this system is similar to the other multistage zeolite dryer systems. The system consists of some adsorbers stages to dehumidify air. The zeolite particles are fluidized in the adsorber. Part of the zeolite particles is withdrawn for regeneration. The activated zeolite is returned to the adsorbers. The cyclones are used to separate air and particles. Of course, it is also an option to apply the multistage rotary wheel system here. The wet product is dried in two dryer stages; in this case a spray and fluidized bed dryer (see Figure 7.6). The spray dryer is used to dry fresh wet product. Exiting spray dryer, the product passes a fluidized bed dryer to finalize product drying.

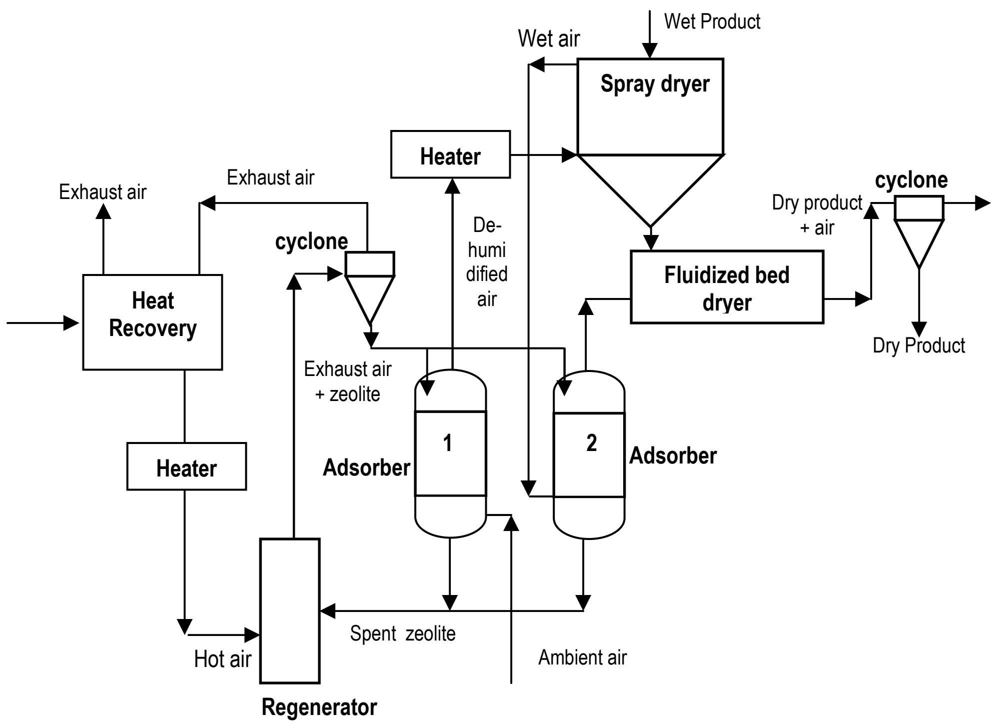

Figure 7.6: Air dehumidified by fluidized bed adsorber for the spray and fluidized bed dryer

4. Perspectives

The potential of adsorption drying with zeolite is evaluated by using a steady state and a dynamic model and also by computational fluid dynamics calculations. The calculations results were confirmed by an experimental evaluation on a one-stage system. All results indicate the same energy performance and the best results are obtained for a ratio between the air flow for drying and the air flow for regeneration equal 4:1. Energy efficiency improves with the number of stages that are applied, but as the energy efficiency improvements are marginal for a high number of stages, a system with 3 stages seems to be most efficient. The energy efficiency values range from 70-80-88% for respectively a one-, two- and three stage system. Further improvement is possible by compressing the regenerator exhaust air which opens the possibility to recover latent heat.

For future development, some options for equipment designs have been discussed. The industry can select the best options for their drying application taking the product properties and the availability of utility units into account. The discussed options are just a start that still requires further modification and detailed dimensions specifications.

According to the obtained impressive results it is expected that zeolite drying will be highly attractive for drying of heat sensitive products such as food, vaccines and herbal medicines. The positive results will boost the development of novel dryers for efficient energy usage and retaining product quality. For the development of novel dryers the model and experimental set-up can be refined further. Furthermore, for the development of novel dryers the sensitivity of the energy efficiency to changes in the operational conditions and product properties will assist the search for an optimal design. In this work minimal attention has been paid to the controllers to be applied, but it would be worthwhile to investigate the potential of advanced control like optimal control, model predictive control and fuzzy control. A special challenge will be the control for efficient start-up, and efficient switching between operational conditions.

Summary

Although drying takes a significant part of the total energy usage in industry, currently available drying technology is often not efficient in terms of energy consumption. Generally, the energy efficiency for drying processes ranges between 20-60% depending on the dryer type and product to be dried. The high energy consumption and low energy efficiency have a high environmental impact due to combustion of fossil fuel or wood used as energy source. Moreover, the sources of fossil fuel are limited, the prices for energy increase and the world wide industrial energy usage rises. In this context the development of efficient drying methods with low energy consumption is an important issue for research in drying technology.

Adsorption drying with zeolite is considered as a potential technique to improve the energy efficiency industrial drying. This approach is based on the dehumidification of the air for drying through adsorption by zeolite. In such way, two main advantages are obtained: 1) the driving force for drying is improved by the lower air humidity, 2) the release of adsorption heat increases the temperature of the air for drying. These advantages result in a highly energy efficient drying system, but after taking the heat for regeneration of spent zeolite into account, the overall energy efficiency improvement is marginal.

The first challenge in this research was to realize an improvement of the energy efficiency for the adsorption drying system with zeolite. To develop a solution, models based on overall mass and heat balance for the dryer, adsorber and regenerator were used. The solution for a better energy efficiency was found by combining the adsorption dryer with a heat recovery system which recovers the energy in the hot off-gas of the regenerator. The energy efficiency for a single stage zeolite dryer operating at 50-70°C with 2-4 heat exchangers for heat recovery is 10-18% higher than that of comparable conventional dryers.

Further improvement was realized by a multistage adsorption dryer system with zeolite. In this system product is dried in a number of succeeding stages. After each stage the exhaust air passes an adsorber where the air is dehumidified before feeding to the next drying stage. The main benefit of the system is that the energy content of the exhaust air is reused several times. Moreover, the released adsorption heat is utilized for the drying in the succeeding stages. The regeneration process requires heat supply and is done for each adsorber or a combination of adsorbers, but with pinch based heat recovery the energy input can be kept low.

Model calculations, using the same balances as in the previous step, were done for co-current, counter-current and cross-current multistage systems. Results showed that the energy efficiency increases with the number of stages and seems most effective for 2-3 stages. The counter-current dryer is the most efficient and achieves an energy efficiency of 88% for a 3-stage system. Compression of the exhaust air from the regenerator makes it possible to recover both sensible and latent heat which can be used to heat ambient air for an extra dryer stage. After

taking into account the energy for compressing air, the energy efficiency achieves 110-120% that implies that the energy usage is halved.

The performance of the multistage zeolite dryer system was also evaluated for lower operational temperature in the range 10-50°C. The dryer was compared with a drying system which uses condensation for air dehumidification and it was found that the energy efficiency of the multistage zeolite dryer system is superior for ambient air temperatures in the range 10-25°C and 50-80% relative humidity. Results showed that the energy efficiency of three stage zeolite dryer is 15-50% higher than that of a conventional condensation dryer.

Till now overall mass and heat balances were used for the calculations and the processes inside the dryer, adsorber and regenerator were ignored. Knowing what happens in the system is essential for further specification and development of dryer, adsorber and regenerator. For this purpose computational fluid dynamic (CFD) calculations were performed for a combined adsorber-dryer-regenerator system. The calculations delivered information on the internal temperature and water content distribution of all units and revealed characteristic phenomena useful to find bottlenecks and to improve the system. The CFD calculations are also powerful to estimate the dimensions and type of equipment for industrial applications of multistage zeolite drying. The technical realization and operation of a multistage dryer with a continuous moving bed of zeolite (CMBZ-dryer) is feasible. Moreover, the energy efficiency obtained from the CFD calculations is comparable to the results obtained from the overall steady state model.

The energy efficiency of a single-stage adsorption dryer using zeolite was experimentally evaluated in a twin-column system working in shift. The columns containing zeolite are alternately used for air dehumidification and for zeolite regeneration. The experimentally obtained energy efficiency corresponded with the model results for the same operational conditions. To extrapolate the experimental results to other operational conditions, a dynamic model for the twin column system was fitted to the data. This model showed that the ratio between air flow for drying and air flow for regeneration, and the ambient relative humidity and temperature affect the energy efficiency the most. The results show that the energy efficiency of the system is around 75% if the ratio between air flow for drying and air flow for regeneration is 4:1.

Options to realize the zeolite dryer system are the twin-column, a continuous moving bed of zeolite or rotating wheel. Systems characteristics are evaluated and compared in a sensitivity analysis. Results showed that the systems have similar energy efficiency performance. Hence, it can be noted that for industrial application, the continuous moving bed of zeolite or wheel system to realize the dryer system.

Samenvatting

Hoewel drogen een belangrijk aandeel heeft in het industriële energieverbruik is de huidige droogtechnologie vaak niet efficiënt in het energieverbruik. De energie efficiëntie varieert tussen de toegepaste droogtechnieken en voor het te drogen product en ligt in het algemeen in de range 20-60%. Het hoge energieverbruik en de lage efficiëntie hebben een grote impact op de omgeving en het milieu door het gebruik van fossiele brandstoffen of hout voor verbranding. De voorraden fossiele brandstoffen zijn beperkt, de energieprijzen stijgen snel en het wereldwijde energiegebruik neemt steeds verder toe. Gezien deze ontwikkelingen is de ontwikkeling van energie efficiënte drogers een belangrijk aandachtsveld voor onderzoek op het gebied van droogtechnologie.

Adsorptiedrogen met zeolieten wordt als een kansrijke techniek gezien om de energie efficiëntie bij industrieel drogen te verbeteren. Hierbij wordt gebruik gemaakt van drooglucht die ontvochtigd wordt door de lucht door een zeolietbed te leiden. Op deze manier worden 2 belangrijke voordelen behaald: 1) de drijvende kracht voor drogen wordt verhoogd door de lagere luchtvochtigheid, 2) de vrijgekomen adsorptiewarmte verwarmt de drooglucht. Deze twee effecten zorgen voor een hoge energie efficiëntie, maar als de energie voor het regenereren van zeoliet in beschouwing wordt genomen is de verbetering maar marginaal.

De eerste uitdaging voor dit onderzoek was dan ook het ontwikkelen van een aanpak om adsorptiedrogen met zeoliet toch energie efficiënt te maken. Voor het ontwikkelen van oplossingen zijn modellen voor de overall massa- en warmtebalansen voor alle units in een adsorptiedroger (droger, adsorber, regenerator, etc.) opgesteld. De oplossing voor een betere energie efficiëntie werd gevonden door het droogsysteem te combineren met een systeem voor terugwinning van warmte uit de uitlaatlucht van de regenerator. De energie efficiëntie voor een droger waarbij een inlaatluchttemperatuur in de range 50-70°C wordt toegepast, is bij het toepassen van 2-4 warmtewisselaars 10-18% beter dan bij vergelijkbare traditionele drogers.

Een verdere verbetering is tot stand gebracht door het toepassen van een meer-traps zeoliet droger. In dit systeem wordt product in verschillende stappen (trappen) gedroogd door ontvochtigde lucht. De lucht die elke trap verlaat wordt elke keer opnieuw ontvochtigd met zeoliet, voordat ze wordt gebruikt voor de volgende droogstap. Het belangrijkste voordeel is dat de energie in de uitlaatlucht van elke stap niet verloren gaat, maar behouden blijft voor de volgende droogstap. Verder draagt de vrijgekomen adsorptiewarmte elke keer bij aan het opwarmen van de drooglucht. Het regenereren van verzadigd zeoliet voor alle adsorbers of combinatie van adsorbers vraagt energie, maar door toepassing van op pinch technologie gebaseerde warmteterugwinning kan de benodigde energie laag worden gehouden.

Modelberekeningen, die gebaseerd zijn op dezelfde balansen als eerder genoemd, zijn uitgevoerd voor meestroom, tegenstroom en kruisstroom meer-traps systemen. De resultaten laten zien dat de energie efficiëntie hoger wordt met het aantal trappen en lijkt het meest effectief voor 2-3 trappen. Het tegenstroom systeem is het meest effectief en bereikt voor een 3-traps systeem een energie efficiëntie van 88%. Comprimeren van de uitlaatlucht van de regenerator maakt het mogelijk om naast de voelbare warmte ook de latente warmte terug te winnen waarmee lucht voor een extra droogtrap kan worden verwarmd. Nadat het energieverbruik van de compressor in rekening wordt gebracht wordt een energie efficiëntie van 110-120% bereikt. Dit betekent dat het energieverbruik bij drogen gehalveerd kan worden.

Het meer-traps droogsysteem is ook geëvalueerd voor drogen met een luchttemperatuur in de range 10-50°C en er is een vergelijking gemaakt met een traditionele droger waarbij de lucht ontvochtigd wordt door condensatie. De resultaten voor de meer-traps droger zijn duidelijk beter als de temperatuur van de aangezogen omgevingslucht in de range 10-25°C ligt en de relatieve luchtvochtigheid van deze lucht tussen 50-80% is. Een 3-traps zeolietdroger heeft dan een 15-50% betere energie efficiëntie.

Tot nu toe zijn overall massa- en warmtebalansen voor de berekeningen gebruikt en zijn de processen binnen de droger, adsorber en regenerator buiten beschouwing gelaten. Kennis wat er in het systeem gebeurd is essentieel voor verdere ontwikkeling van de apparatuur. Computational fluid dynamics (CFD) berekeningen zijn uitgevoerd voor een gecombineerd droger-adsorber-regenerator systeem. Deze berekeningen geven inzicht in de verdeling van temperatuur en watergehalte in de apparatuur en zijn van belang om bottlenecks in het systeem op te lossen. Verder kunnen ze gebruikt worden voor de dimensionering van meer-traps installaties voor industrieel gebruik. De technische realisatie van continu getransporteerd zeoliet bed (CMBZ-droger) blijkt op basis van de berekeningen haalbaar. Verder tonen de berekeningen aan dat energie efficiëntie volgens deze gedetailleerde berekeningen overeen komen met voorgaande berekeningen die gebaseerd zijn op de overall balansen.

De energie efficiëntie van een een-traps adsorber droger met zeoliet is experimenteel vastgelegd in een twin-kolom systeem. De kolommen, die allebei een bed met zeoliet bevatten, worden afwisselend gebruikt voor lucht ontvochtigen en zeoliet regeneratie. De experimenteel bereikte energie efficiëntie komt overeen met de modelberekeningen onder vergelijkbare condities. Om voorspellingen te doen voor andere operationele omstandigheden is een dynamisch model van het twin-kolom systeem gefit met de verkregen data. Dit leverde het inzicht dat de verhouding tussen de luchtstroom die via de adsorber naar de droger gaat en de luchtstroom die gebruikt wordt voor regeneratie, de omgevingstemperatuur en relatieve luchtvochtigheid het meeste effect hebben op de energie efficiëntie. Voor een verhouding tussen de luchtstromen 4:1, wordt een energie efficiëntie van 75% bereikt.

Het twin-kolom systeem, het continu getransporteerd zeoliet bed en een roterend wiel zijn mogelijkheden om de meer-traps zeoliet droogsysteem voor industriële toepassing te realiseren. De systeemkarakteristieken blijken bij een gevoeligheidsanalyse vergelijkbaar en daarom zijn het continu getransporteerd zeoliet bed en een roterend wiel goede opties om het systeem voor industriële toepassing te realiseren.

Ringkasan

Pengeringan memerlukan energi yang besar dalam industri, namun teknologi pengeringan yang ada belum cukup efisien. Umumnya efisiensi energi berkisar antara 20-60% tergantung dari jenis pengering dan produk yang dikeringkan. Hal ini menyebabkan proses menjadi boros energi dan meningkatkan emisi gas pencemaran hasil pembakaran bahan bakar fosil. Terlebih lagi dengan terbatasnya sumber-sumber energi fosil, dan melambungnya harga minyak mentah dunia, serta adanya industrailisasi, energi untuk proses pengeringan akan semakin mahal. Dalam kontek ini maka pengembangan energi pengeringan yang efisien menjadi hal yang sangat penting.

Proses pengeringan dengan cara adsorpsi air dari udara menggunakan zeolite dipertimbangkan menjadi pilihan yang mampu mereduksi konsumsi energi dengan atau meningkatkan efisiensi proses. Hal ini disebabkan oleh dua hal yaitu: 1). udara akan berkadar air lebih rendah karena diserap zeolite sehingga menaikkan kapasitas udara untuk membawa uap air dari bahan basah, 2). suhu udara selama proses penyerapan meningkat sehingga mengurangi konsumsi energi dari unit pemanas. Bagaimanapun, setelah diperhitungkan dengan panas untuk meregenerasi zeolite yang telah jenuh, peningkatan efisiensi ini sangat sedikit. Selain itu, biaya proses menjadi makin tinggi karena proses regenerasi perlu suhu yang lebih tinggi.

Tantangan pertama dalam riset ini adalah merealisasikan peningkatan efisiensi proses pengeringan menggunakan zeolit. Yang pertama dilakukan yaitu perhitungan neraca masa dan energi dari seluruh proses mulai dari adsorbsi, regenerasi, dan pengeringan. Dari neraca tersebut dapat diidentifikasi aliran panas keluar yang dapat dimanfaatkan kembali. Pemanfaatan panas terbuang ini dilakukan dalam rangkaian alat penukar panas dimana aliran udara panas yang terbuang dari regenerator digunakan untuk memanasi udara luar yang digunakan untuk proses regenerasi. Adanya unit ini maka kebutuhan panas untuk proses regenerasi menjadi lebih hemat. Dengan menggunakan 2-4 alat penukar panas pada suhu pengeringan 50-70°C, efisiensi panas dapat ditingkatkan 10-18% diatas efisiensi pengering konvensional.

Design lanjut telah dilakukan dengan merancang pengeringan *multistage*. Pada tahap ini, air basah keluar dari unit pengering diproses ulang dalam unit adsorber untuk pengeringan tahap berikutnya. Cara ini dilakukan berulang tergantung dari jumlah tahapan yang dirancang, sehingga panas yang terbuang dari pengering sebelumnya dapat dimanfaatkan total untuk pengering berikutnya. Selain itu panas yang dibebaskan juga semakin besar, dengan meningkatnya kandungan air dalam umpan adsorber. Sementara itu proses regenerasi zeolite jenuh memerlukan energi yang besar, namun dengan adanya unit untuk pemanfaatan panas kembali, total panas yang diperlukan dapat diminimalkan.

Hasil perhitungan menunjukan bahwa efisiensi proses pengeringan menjadi 88% untuk 3 tahap dengan hanya memanfaatkan 16-20% energi terbuang. Untuk mendapatkan efisiensi yang

lebih tinggi, digunakan kompresor agar dapat memanfaatkan panas laten uap air di dalam udara yang keluar regenerator. Namun setelah diperhitungkan dengan energi kompresor, peningkatan efisiensi tidak diperoleh. Opsinya adalah menggunakan sisa panas hasil kompresi untuk pemanasan pengering lainnya, sehingga diperoleh efisiensi keseluruhan sebesar 110-120% yang menunjukkan energi tersebut adalah setengah dari yang digunakan pada pengering konvensional.

Performansi pengeringan multi tahap juga telah diuji pada berbagai kondisi iklim dan temperature operasi yang lebih rendah 10-50°C. Efisiensi energi yang dicapai juga dibandingkan dengan pengering suhu rendah menggunakan condenser. Hasil menunjukkan bahwa efisiensi energi sistim pengeringan menggunakan zeolite yang dioperasikan dengan umpan suhu luar 10-25°C kelembaban relatif 50-80%, dapat lebih tinggi 15-50% daripada pengeringan bersuhu dingin konvensional.

Pada tiga penelitian diatas, proses fenomena yang terjadi didalam pengering, adsorber dan regenerator diabaikan dengan kata lain sistim perhitungan menggunakan model tunak serta semua unit proses diasumsikan tercampur dengan sempurna. Desain lebih detil telah dilakukan menggunakan model komputasional dinamika fluida dalam satu dan dua dimensi, untuk mengetahui fenomena yang terjadi di dalam adsorpsi, regenerasi dan pengeringan yang akan digunakan untuk menentukan dimensi alat proses. Perhitungan menunjukkan bahwa model dua dimensi memberikan informasi profil suhu dan kandungan air selama proses, baik dalam fase padat maupun gas,serta dimensi alat. Selain itu, desain alat sistim yang sederhana dapat diketahui yaitu menggunakan zeolite yang bergerak secara kontinyu dengan efisiensi yang sebanding dengan hasil perhitungan dalam kondisi tunak.

Pendekatan konsep diatas diuji menggunakan pengeringan zeolite dengan satu tahap. Dalam pengambilan data menggunakan alat ini, efisiensi energi dihitung berdasarkan total bersih energi yang diperlukan, serta energi yang digunakan pada unit pengering. Data-data ini juga digunakan untuk memvalidasi model dinamika dari proses. Dengan perbandingan udara untuk pengeringan dan udara untuk regenerasi zeolite 1:1, diperoleh efisiensi total 50-55%. Hasil yang sama juga diperolah pada perhitungan menggunakan model tunak maupun dinamik. Dengan ekstrapolasi kondisi menggunakan model dinamik, efisiensi sekitar 75% diperoleh pada perbandingan udara untuk pengeringan dan udara untuk regenerasi 4:1, dimana hasil ini bersesuaian dengan hipotesa awal perhitungan menggunakan sistim tunak.

Berdasarkan hasil-hasil diatas maka sistim pengeringan dirancang menggunakan zeolite yang digerakan dengan belt atau roda berputar yang berisi dengan zeolite. Penggunaan ini mampu mengurangi biaya konstruksi untuk operasi dan mengontrol proses. Untuk verifikasi, sistim ini dibandingkan dengan sistim shif hasil eksperimen pada satu dan dua tahap proses pengeringan berdasarkan karakter proses dan efisiensi energinya. Hasil menunjukkan bahaw kedua sistim itu memiliki kesamaan untuk kedua hal diatas. Oleh karena itu disimpulkan bahwa zeolit dalam belt atau roda berputar dapat digunakan untuk menggantikan model shif pada pengembangan skala besar.

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Curriculum Vitae

Mohamad Djaeni was born in Kebumen, Indonesia, on February, 7th, 1971. He graduated from Diponegoro University, Semarang Indonesia, in Bachelor Degree of Chemical Engineering at 1995. After graduating, he worked as a lecturer in the Department of Chemical Engineering, Faculty of Engineering, Diponegoro University. Two years later, he enrolled in the MSc program at the University Technology Malaysia and obtained the degree Master of Engineering in for his work in Chemical Process Control in 1999. The master research consists of the design of unit operations using dynamic models, identifying process characteristics, selecting input-output pairing for process control, and configuring a plant wide control system.

Since December 2004 he was admitted for the doctoral research work in the Systems and Control Group, Department of Agrotechnology and Food Science, Wageningen University. The topic of the research was the development of an efficient zeolite dryer for heat sensitive products. This work is extensively decribed in this thesis.

Parallel with the doctoral research, he has joined several trainings, and assisted for the course on Control Engineering and Process Control. Besides that he has been active member of Indonesian Student Association (ISA) in the period 2005-2008, and was elected as vice president of ISA for 2007/2008. Furthermore, he was co-chairman of the organizing committee for the Indonesian Student Scientific Meeting 11 (ISSM11) held on May 13-15, 2008 at TU Delft University under collaboration with ISA Wageningen, Delft, ISTECS chapter Europe, TU Delft University, and Embassy or Republic Indonesia.

List of Publications

International Journal

1. Djaeni, M.; Bartels P.V.; Sanders J.P.M.; van Straten, G.; van Boxtel, A.J.B. Process Integration for Food Drying with Air Dehumidified by Zeolite. Drying Technology 2**007**, 25 (1), 225-239
2. Djaeni, M.; Bartels P.V.; Sanders J.P.M.; van Straten, G.; van Boxtel, A.J.B. Multistage Zeolite Drying to Enhance Energy Efficiency of Food Drying. Drying Technology **2007**, 25 (6), 1053-1067
3. Djaeni, M.; Bartels P.V.; Sanders J.P.M.; van Straten, G.; van Boxtel, A.J.B. CFD for Multistage Zeolite Dryer Design. Drying Technology **2008**, 26 (4), 487-502
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3. Djaeni, M.; Bartels P.V.; Sanders J.P.M.; van Straten, G.; van Boxtel, A.J.B. Design of Multi Tray Low Temperature Drier Using Air Dehumidified by Zeolite for Heat Sensitive Products. NPS 7, October 29-30, 2007; Veldhoven, The Netherlands
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1. Van Boxtel, A.J.B., Bartels, P.V., Djaeni, M., Sanders, J.P.M., Van Straten, G. Assembly and Method for Drying a Product. Submitted to Netherlands Patent No. P6012219NL
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Overview of completed training activities

Name of the course	Graduate school/Institute	Year
a. Discipline specific activities		
Sustainable process design	OSPT	2005
Advanced process integration & plant-wide control	OSPT	2005
Physical modelling	SENSE	2005
Particle based modelling	OSPT	2006
Reaction kinetics in food products	VLAG	2006
Systems and control theory	SENSE	2006
Adsorptive processes	OSPT	2007
NPT Congress Veldhoven	OSPT	2007
ADC07 Hong Kong	HKUST	2007
b. General courses/activities		
Time planning and project management	PE & RC	2005
Intermediate tutored self study course English	CENTA	2006
PhD presentation skills	CENTA	2006
VLAG AIO week	VLAG	2006
PhD Scientific writing	CENTA	2007
Business competition	WBS	2007
Indonesian Student Scientific Meeting, TU Delft	ISSM	2008
c. Optional		
Writing research proposal		2005
Signal & systems modelling	SCO/WU	2005
Renewable resources for the bulk-chemical industry	VPP	2007