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ENERGY EFFICIENT POWDER PRODUCTION BY CLOSED-LOOP SPRAY DRYING

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Abstract: Closed-loop dryers are able to reduce the energy consumption in milk powder production up to 60% compared to current practice. Application of monodisperse droplet atomizers eliminates the presence of fines in the exhaust air of spray dryers. It allows the recirculation of the exhaust air over the dryer and the recovery of latent heat. For recirculation, the air is dehumidified with a membrane contactor using saturated salt solutions, or a zeolite system. During dehumidification heat is released while energy is needed for regeneration of the adsorber. By heat integration of the adsorber-regenerator system with the dryer or a related process, a significant improvement of energy efficiency can be achieved. In this work we present four configurations for closed-loop spray drying. For each system simultaneous optimization of the operational conditions and the heat exchanger network is applied for optimal energy recovery. The results for milk powder production showed that, compared to the current practice, simultaneous optimization for closed-loop dryer system results in a reduction of energy consumption from 38% up to 62%.

Keywords: Spray drying, monodisperse droplet, air dehumidification, pinch analysis, system optimization.

INTRODUCTION

In the food industry 29% of the total energy consumption is used for thermal processing, with drying as a major user (Okos et al. 1998). In current spray drying systems energy is lost with the exhaust air, both in the form of latent and sensible heat. Several authors have studied the possibilities for energy recovery from the exhaust air by heat integration and air recirculation over the dryer (Atkins, Walmsley, and Neale 2011; Golman and Julklang 2014; Walmsley et al. 2013). The main limitation for energy recovery are the fine particles (fines) in the dryer exhaust air which make heat recovery inefficient. Energy is lost in filter systems used for the removal of these fines and, furthermore, the fines cause fouling on heat exchanger surfaces.

Monodisperse droplet drying has the potential for product drying with (near) elimination of fines in the exhaust air. Recent papers show promising results of monodisperse droplet atomizers (Deventer, Houben, and Koldeweij 2013; Fu et al. 2011; Rogers et al. 2012). Absence of fines in the exhaust air enables recirculation of air over the dryer, and heat integration.

The temperatures of exhaust air of a spray dryer for milk powder production are in the range of 60 – 90°C, and the moisture content is between 0.04 – 0.05 kg water per kg air. Dehumidification is, therefore, required for air recirculation and recovery of latent heat. Two systems are available for air dehumidification: 1) contact sorption systems with an adsorbent like zeolite or silica, and 2) membrane contactors with a hygroscopic absorbent like lithium bromide.

Contact sorption systems contain adsorbents with a high affinity for water. Zeolites have proven to be efficient for higher temperatures, which makes them a good candidate for dehumidification of exhaust air of the spray dryer. The potential for energy savings with zeolites has been shown by Boxtel et al. (2012), Djaeni et al. (2007) and Goldsworthy et al. (2015). Membrane contactors are currently used for degassing and air conditioning systems (Bergero and Chiari 2010; Kneifel et al. 2006; Li and Chen 2005).

Water vapor in moist air is transferred through a hydrophobic membrane to a saturated lithium bromide solution (brine). The water vapor partial pressure difference is hereby the driving force. As the vapor condenses and is absorbed by the brine, latent heat of the water vapor is released, raising the temperature in the system.

During dehumidification energy is released, but regeneration of the adsorbents (zeolite or lithium bromide) requires energy. The outlet streams of the dehumidification and regeneration units contains a non-negligible amount of energy. Heat integration is, therefore, important to make closed-loop dryers energy efficient. Pinch analysis is a well-established method to design an optimal heat exchanger network, and thus minimizing external utilities (Kemp 2007).

The pinch approach is a step-wise procedure in which operational conditions like flows and temperatures are established first, after which the heat exchange network is defined according to pinch rules. The drawback of this method is that the operational conditions are not optimized in connection to the heat exchange network. Atuonwu et al. (2011) applied a simultaneous approach by mixed-integer non-linear programming (MINLP) where the pinch analysis and optimization of operational conditions were combined in one step. It resulted in a 15% lower energy consumption compared to the results of the standard pinch approach. An alternative to the MINLP approach is NLP approach which is applied in in this work.

In this work we illustrate that the energy efficiency of a closed-loop monodisperse-droplet dryer with simultaneous optimized heat integration results in a significant reduction of the external energy consumption.

PROCESS DESCRIPTION

Fig. 1 depicts the total system which concerns pre-drying steps in which the milk is preheated and concentrated. Then the milk is atomized in a closed-loop monodisperse spray dryer with air dehumidification. The air dehumidification consists of an adsorber part (either a membrane contactor or zeolite), regeneration and optional cooling or heating.

Steady-state models for mass and energy balances of all sub units in this system were used. All energy balances are based on the following enthalpy equations for liquids/solids and for air:

$$H_{l/s} = F_{l/s} \cdot (c_{p,l/s} \cdot x_{l/s} + c_{p,w} \cdot x_w) T_{l/s} \quad (1)$$

$$H_a = F_a\left(c_{p,a} + y_a \cdot c_{p,v}\right) T_a \quad (2)$$

Pre-drying

Milk in a medium scale factory with a milk flow of 10,000 kg milk per hour, solid content of 9% and temperature of 10°C is preheated and concentrated. The amount of energy that can be recovered from the adsorber-regeneration system is not enough for concentration, but is useful for pre-heating. Therefore the requirements for the pre-heating step are taken into account. Milk is heated up from 10°C to 60°C, the energy requirements are based on Eq. 1. Next, milk is concentrated from 0.91 kg water/kg milk to 0.5 kg water/kg milk, but energy requirements for concentration are not considered in this work.

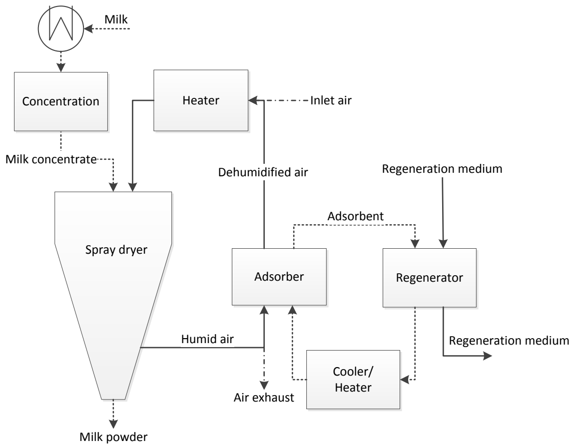

Fig. 1. Schematic representation of a closed-loop dryer for milk powder production. The adsorber can either be the membrane contactor or zeolite system.

Monodisperse spray dryer

In the dryer, hot air contacts the atomized droplets and mass and energy exchange take place. The water balance is:

$$F_a \cdot y_{a,in} + F_{m,in} \cdot x_{w,in} = F_a \cdot y_{a,out} + F_{m,out} \cdot x_{w,out} \quad (3)$$

The final water content of the milk powder ($x_{w,out}$) is set to 0.035 kg water/kg powder. The moisture content of the inlet air ($y_{a,in}$) depends on the dehumidification process. The moisture content in the exhaust air is:

$$y_{a,out} = RH_{out} \cdot y_{sat} \quad (4)$$

Where $y_{a,out}$ depends on the outlet air temperature, which follows the enthalpy line of the dryer, and the vapor saturation line (y_{sat}) in the psychometric chart. For milk powder with 3.5% moisture, RH_{out} is about 10%, which is a common value in milk powder production with spray dryers.

The overall energy balance over the dryer is:

$$H_{a,in} + H_{m,in} = H_{a,out} + H_{m,out} \quad (5)$$

Membrane contactor

In the membrane contactor the air flow is separated from the brine by a hydrophobic membrane which is only permeable for water vapor. The brine heats up due to the released heat of condensation. Internal cooling of the membrane contactor is used to recover this heat. The used mass and enthalpy balances are:

$$F_a \cdot y_{a,in} + F_{LiBr} \cdot x_{w,in} = F_a \cdot y_{a,out} + F_{LiBr} \cdot x_{w,out} \quad (6)$$

$$H_{a,in} + H_{LiBr,in} + H_{c,in} = H_{a,out} + H_{LiBr,out} + H_{c,out} \quad (7)$$

$$P_{air,in} - P_{LiBr,out} = P_{air,out} - P_{LiBr,in} \quad (8)$$

For estimations on heat transfer between the air, membrane, and brine, the Maxwell-Stefan equation is used (Krishna and Wesselingh 1997). The brine temperature on the outlet is related to the vapor pressure gradient along the membrane contactor (Eq. 8). The pressure gradient is assumed the same everywhere along the membrane.

From the heat and mass transfer equations follow the decision variables that influence the performance of the membrane contactor. I.e. the difference in temperature (ΔT_{mc}) between the air towards the adsorber and the brine in, and the difference between water concentration (Δx_{mc}) of the brine in and out.

There are two options for regeneration of the brine: 1) via a two effect evaporator, or 2) with superheated steam.

For regeneration of the brine by evaporation the required amount of energy is given by:

$$H_s = \frac{F_{LiBr}\Delta x_{LiBr}}{1 + \frac{H_{v1}}{H_{v2}}} \cdot \frac{H_{v1}}{F_s} \quad (9)$$

Where H_v is the heat of evaporation, which depends on the corresponding temperatures, and F_s the amount of steam required for the first effect.

The energy required to release the water from the brine by superheated steam is given by the enthalpy balance with superheated steam as regeneration medium:

$$H_{rm,in} + H_{LiBr,in} = H_{rm,out} + H_{LiBr,out} \quad (10)$$

Where the enthalpy of the superheated steam (H_{rm}) depends on its temperature (T_{shs}) and pressure.

Depending on the operational conditions, the brine is cooled or heated after regeneration.

$$H_{LiBr,in} + Q_{heat} = Q_{cool} + H_{LiBr,out} \quad (11)$$

Zeolite

The zeolite adsorption system consists of a wheel system with three separate sections: 1) adsorption, 2) regeneration, and 3) cooling or heating. These sections are modeled as separate units.

For the adsorption section the following equations are applied:

$$F_a \cdot y_{a,in} + F_z \cdot x_{w,in} = F_a \cdot y_{a,out} + F_z \cdot x_{w,out} \quad (12)$$

$$H_{a,in} + H_{z,in} - H_{des} = H_{a,out} + H_{z,out} \quad (13)$$

Regeneration is possible with either hot air or superheated steam. Both based on the same balance as presented in Eq. 10. The same accounts for the heating or cooling the zeolite might require after regeneration, this is based on the balance similar as given in Eq. 11.

OPTIMISATION

The four different scenarios, which depend on the type of adsorber and the regeneration medium, are given in Table 1.

Table 1. Overview of the four different scenarios with the membrane contactor (MC) or zeolite as air dehumidifier, and different regeneration media.

Scenario	Adsorber	Regeneration medium
1	MC	Evaporator
2	MC	Superheated steam
3	Zeolite	Hot air
4	Zeolite	Superheated steam

As the dryer is operated as a closed-loop system and for a low energy consumption is aimed, the degree of dehumidification and the heating of the air from the adsorber to the dryer inlet temperature are important aspects. Therefore, the decision variables for all four scenarios are the dryer inlet temperature ($T_{a,in}$) and moisture content of the air into dryer ($y_{a,in}$), and the inlet ($T_{rm,in}$) and outlet ($T_{rm,out}$) temperature of the regeneration medium. For the scenarios with the membrane contactor the concentration difference of the LiBr solution over the module (Δx_{mc}), and the temperature difference over the module (ΔT_{mc}) are additional decision variables. For the application of the zeolite, the inlet temperature of the zeolite into the adsorber ($T_{z,in}$) is a decision variable. The upper and lower bounds for each decision variable (DV) are listed in the Appendix.

The optimization problem is defined as:

$$min(total\ external\ energy) \quad (14)$$

s.t. $mass\ and\ energy\ balances\ (Eq. 1 - 13)$

$lower\ bound < DV < upper\ bound$

The standard procedure for heat integration is to optimize a process on its operational conditions, and then to apply pinch analysis to find options for heat integration. This approach, however, does not reach full optimality of the defined process system. In other words after heat integration the optimized operational conditions of the process system may not be the optimal ones for the process system with heat integration. Therefore by simultaneous optimization of operational conditions and heat integration an additional step in energy reduction can be made, as shown by Atuonwu et al. (2011). The procedure that has been applied here is that, after identification of potential hot and cold streams, all possible heat exchanger networks with a minimum temperature difference of 10°C were defined. Then all these networks were optimized by NLP, and for each scenario the best network was selected.

It should be noted that, depending on the operational conditions in this system, some streams could be classified as either hot or cold streams. For example the brine may need cooling or heating after regeneration. The switch between these functionalities was included in the optimization procedure.

RESULTS

For the four scenarios different decision variables were applied. The optimized decision variables are presented in Table 2, corresponding sizes of the streams are listed in the Appendix.

Table 2. List of the optimal values for each decision variables per scenario.

	Scenario			
DV	**1**	**2**	**3**	**4**
$T_{a,in}$ [°C]	180	180	180	180
$y_{a,in}$ [kg/kg]	0.009	0.006	0.01	0.01
Δx_{mc} [kg/kg]	0.07	0.03	-	-
ΔT_{mc} [°C]	1	1	-	-
$T_{z,in}$ [°C]	-	-	100	100
$T_{rm,in}$ [°C]	130	235	200	250
$T_{rm,out}$ [°C]	50	195	-	200

Scenario 1 concerns the membrane contactor with two-effect evaporator for the regeneration of the brine. The two hot streams are the vapor/condensate from the evaporator and the cooling water from the membrane contactor. The quality of both is not sufficient for the energy supply of the steam used in the first effect. However, the quality is satisfactory to pre-heat milk from 10 to 55°C, to partly heat the dehumidified air and to partly heat the brine that leaves the evaporator to the adsorber temperature. The optimal heat exchanger network is given in Fig. 2. The decision variables are all at or close to the upper and lower boundaries. The spray dryer inlet air temperature for drying is at the lower boundary (180°C). Having the temperature at this value implies a minimum amount of heating of the recirculated air. This is a remarkable outcome compared to conventional spray drying where the air inlet temperature is always at the upper boundary. In total 1.6 MJ per kg milk powder is recovered in the network and the total energy for this scenario is 3.1 MJ per kg milk powder.

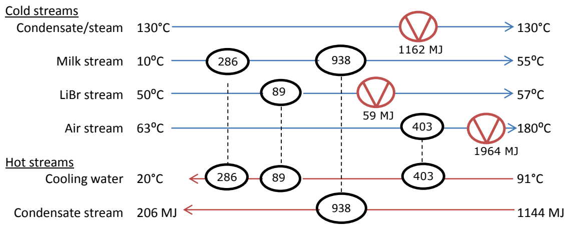

Fig. 2. Heat exchanger network of scenario 1, with the corresponding temperatures and amounts of heat exchanged.

Scenario 2 is the membrane contactor combined with superheated steam regeneration. The heat exchanger network is shown in Fig. 3. In contrast to the previous scenario the brine is a hot stream, and requires cooling after regeneration. The use of superheated steam makes this scenario interesting as the water removed from the brine can be fully utilized as additional steam. This is a big advantage compared to the evaporator in scenario 1. The generation of superheated steam requires high amounts of energy. Nevertheless after heat integration, this scenario resulted in the lowest amount of external energy of all four tested scenarios, 2.3 MJ per kg milk powder. The low energy consumption is result of a high degree of energy recovery (4.0 MJ per kg milk powder). Without successful heat integration the energy consumption is high. Regeneration of the membrane contactor with superheated steam might be a bottleneck, as it is not known yet whether the membrane module is able to withstand high temperatures (250 °C).

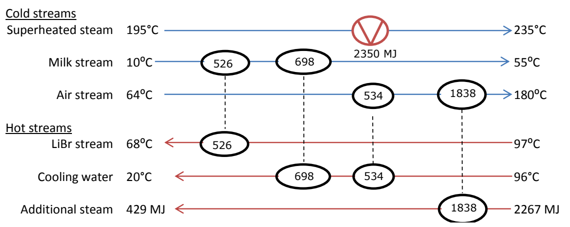

Fig. 3. Heat exchanger network of scenario 2, with the corresponding temperatures and amounts of heat exchanged.

In scenario 3 the zeolite system was optimized with hot air as regeneration medium. The optimal settings of operational variables are given in Table 1. Heat integration of this scenario is relative straight forward (see Fig. 4). The regeneration air leaving the regenerator has a temperature of 105°C, and therefore the only possible heat exchange is with the milk stream. All other heating and cooling duty require external energy. The air temperature after dehumidification (about 140°C) differs strongly from that of scenario 1 and 2 (63 – 64°C). The released adsorption heat in scenario 3 is for a major part transferred to the air, while in scenario 1 and 2 the energy is released in the brine solution, and mainly transferred to the cooling water, and not to the air. This scenario also confirms that lower drying air temperatures (180°C) are beneficial in terms of energy reduction with a zeolite system. Higher drying air temperature results in higher consumption of external energy, because more heating is needed to reheat the air after dehumidification to reach the air inlet temperature. Additionally the zeolite will require more cooling since the temperature after regeneration will be elevated as well. The total energy consumption for this scenario is 3.7 MJ per kg milk powder, the amount of recovered heat is 1.2 MJ per kg milk powder.

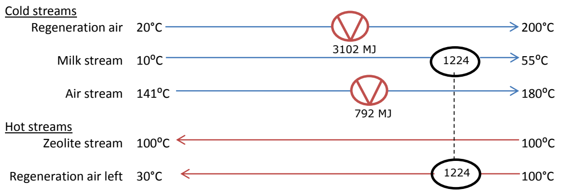

Fig. 4. Heat exchanger network of scenario 3, with the corresponding temperatures and amounts of heat exchanged.

As shown by (Boxtel et al. 2012) superheated steam is more energy efficient in the regeneration of zeolites compared to regeneration with hot air. Scenario 4, therefore, consists of a zeolite system with superheated steam regeneration. Similar to previous scenario, the dehumidification is not very deep, i.e. $y_{a,in\,d} = 0.01$ kg water per kg air (see Table 1). The effect of changing humidity in the air flow to the dryer is very small. Changing the humidity to 0.001 kg per kg dry air results in only 0.5% rise of the energy consumption. This scenario is also most energy efficient with the drying air temperature at the lower bound of 180°C. With energy recovery of 4.8 MJ per kg milk powder, the total energy requirement for this configuration is 2.6 MJ per kg milk powder. The majority is required for the upgrading of the superheated steam as is seen in Fig. 5.

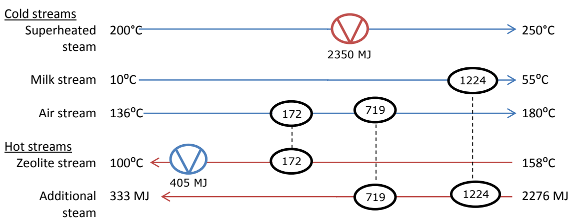

Fig. 5. Heat exchanger network of scenario 4, with the corresponding temperatures and amounts of heat exchanged.

DISCUSSION

The energy requirements for all scenarios are visualized in Fig. 6 where the proposed new process configurations are compared to a benchmark. The energy consumption for the benchmark concerns the pre-heater and spray dryer. The energy consumption in these two steps is 1.2 and 4.8 MJ/kg milk power respectively (Ramírez, Patel, and Blok 2006). The energy consumption with and without heat integration is shown. The results show that heat integration is for all considered closed-loop drying systems essential to reach low energy consumption. The savings for the different scenarios range from 38 to 62% energy compared to the benchmark.

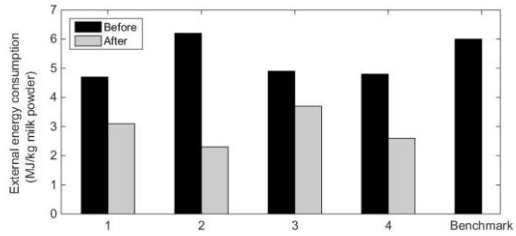

Fig. 6. External energy requirements before and after heat integration.

The total energy consumption in scenario 1 and 3 is higher compared to that of scenario 2 and 4 respectively. The main difference between these scenarios is that in scenario 1 and 3 the quality of the hot streams is not sufficient to heat the dehumidified air to the requested dryer temperature. In scenario 2 and 4 the use of superheated steam as regeneration medium results in a high quality hot stream, which is able to heat the dehumidified air to the requested dryer temperature.

When comparing scenario 2 and 4, it is shown that in scenario 2 more energy is recovered. This has two reasons: 1) the zeolite requires external cooling, and 2) the membrane contactor has a higher energy requirement before heat integration. After regeneration the zeolite used in scenario 4 has to be cooled down to 100°C. This is not possible by heat exchange with another cold stream, as zeolites are solids, and therefore require direct contact. Scenario 2 has the advantage that cooling of the brine solution can be achieved by heat integration. Secondly, the higher energy demand before heat integration in scenario 2 is mainly caused by the lower temperature of the dehumidified air (63°C compared to 136°C in scenario 4). This difference is caused by the heat released and transferred in the adsorber. In the membrane contactor the heat is released in the brine and transferred to the cooling water, only a minor part is transferred back to the air phase. While in the zeolite the released heat results in a temperature rise of both the air and the zeolite. Nevertheless the total external energy requirement of scenario 2 is after heat integration favorable.

Membrane contactor systems at elevated temperatures (200 – 250°C) are not yet commercially available, and therefore scenario 2, with the lowest energy requirements, is still under discussion.

CONCLUSION

Elimination of fines in the exhaust air of spray dryers enables energy efficient closed-loop dryer systems. Heat integration is, however, essential to make the system highly energy efficient. Four different optimized scenarios realize energy savings between 38 – 62% energy compared to the benchmark. The scenario with the lowest external energy requirements, corresponding to a reduction of 62%, is scenario 2, which consists of the membrane contactor and regeneration with superheated steam. However, for this scenario commercial membranes have to be developed. This work also demonstrates the role of simultaneous optimization of the operational conditions and heat exchanger network to reach higher energy reduction.

NOMENCLATURE

Variables

c_p	Specific heat capacity	kJ kg^{-1}°C^{-1}
F	Flow	kg h^{-1}
H	Enthalpy of a stream	kJ
k	Heat transfer coefficient	Wm^{-2}K^{-1}
P	Vapor pressure	Pa
RH	Relative humidity	-
T	Temperature	°C
x	Component content of stream	kg kg^{-1}
y	Moisture content of air stream	kg kg^{-1}dry air

Subscripts

a	Air
cool	Cooling requirement
des	Desorption
evap	Evaporator
heat	Heating requirement
in	Inlet stream
l/s	Liquid or solid
LiBr	Lithium bromide (also referred to as brine)
m	Milk
out	Outlet stream
rm	Regeneration medium
s	Steam
sat	Saturation
shs	Superheated steam
v	Vapor
w	Water
z	Zeolite

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APPENDIX

Table A1. List of the optimal values for each decision variables per scenario.

DV	**Lower bound**	**Upper bound**
$T_{a,in}$ [°C]	180	220
$y_{a,in}$ [kg/kg]	0.001	0.1
Δx_{mc} [kg/kg]	0.01	0.1
ΔT_{mc} [°C]	1	20
$T_{z,in}$ [°C]	20	100
$T_{rm,in}$ [°C]	200	250
$T_{rm,out}$ [°C]	150	200

Table A2. Summary of the sizes of each stream for each scenario, given in kg dry product per hour, or kg steam per hour.

Stream	**1**	**2**	**3**	**4**
F_m	1000	1000	1000	1000
F_a	17035	19262	20003	20003
F_z	-	-	5990	8605
F_{LiBr}	5638	7166	-	-
F_{rm}	508	3000	16908	23921

Table A3. Overview of values for constants and process conditions.

Parameter	**Value**
Absolute pressure [Pa]	101325
Heat capacity dry air [kJ/kg°C]	1
Heat capacity dry matter of milk [kJ/kg°C]	1.54
Heat capacity dry zeolite [kJ/kg°C]	0.836
Heat capacity water [kJ/kg°C]	4.18
Heat capacity water vapour [kJ/kg°C]	1.93
Heat of evaporation [kJ/kg]	2500