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Closed-loop spray drying solutions for energy efficient powder production

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ABSTRACT

This paper introduces a closed-loop dryer system to reduce the energy consumption for milk powder production. The system is based on a monodisperse droplet atomizer which reduces the amount of fines in the exhaust air, and allows dehumidification and recirculation of the air over the dryer. In this way the latent and sensible heat from the dryer exhaust are recovered. Two adsorbent systems for dehumidification are discussed; a membrane contactor with a liquid desiccant, and a zeolite sorption wheel. Four configurations for closed-loop spray drying are simulated and optimized. By heat integration of the adsorber-regenerator system with the dryer and preceding concentration step, the energy consumption is significantly reduced to 4.9 MJ heat per kg milk powder. The final heat integration solutions were obtained by simultaneous optimization of the operational conditions and the heat exchanger network based on pinch analysis.

Industrial relevance: Drying is an energy intensive operation in processing. To comply with the upcoming regulations that arise from the EU goals for sustainable development, the energy consumption of drying processes should be reduced drastically. Emerging technologies are the key for the next step in energy efficiency improvement. A closed-loop spray drying system for milk powder production is simulated and optimized in this work. The proposed technologies are: monodisperse droplet drying, membrane contactor and a zeolite wheel. By applying air dehumidification and heat integration the latent and sensible heat are recovered from the exhaust air. The energy consumption for milk concentration and spray drying has the potential to be lowered from 8.4 to 4.9 MJ heat per kg milk powder. Although milk powder has been considered, the proposed system is also applicable to other food products, as well as in the (bio)chemical, pharmaceutical and paper industry.

1. Introduction

Thermal processes are responsible for 29% of the total energy consumption in the food industry (Okos, Rao, Drecher, Rode, & Kozak, 1998). Spray drying systems are the main energy consumer in powder production. The energy efficiency of spray drying has been improved over the last decades by the introduction of multi-stage drying with fluidized bed dryers, air pre-treatment, heat pumps, and the optimization of the processes and operational conditions to a full extend (Ramirez, Patel, & Blok, 2006; Walstra, Geurts, Noomen, Jellema, & Boekel, 1999; Westergaard, 2004). Furthermore heat recovery and integration of current spray drying processes, like the production of milk powder, has been studied (Atkins, Walmsley, & Neale, 2012; Walmsley, Walmsley, Atkins, Neale, & Tarighaleslami, 2015). However, to reach the energy ambitions of the EU to reduce the energy consumption with 27% in 2030, and even more in the following decades (European Commission, 2011), incremental improvements in energy efficiency, by additional optimization, do not satisfy this requirement. Large steps forwards, which can be achieved by introducing emerging technologies, are needed (Moejes & van Boxtel, 2017). An important development to meet the future requirements on the energy consumption in milk powder production is the energy efficient concentration of milk prior to the spray dryer. Walmsley, Atkins, Walmsley, and Neale (2016) show that application of mechanical vapor recompression (MVR) with optimal heat integration can potentially reduce the energy consumption per kilogram of powder by 78%. It is also demonstrated that with current state of the art technology the energy consumption can be reduced to 5.2 MJ per kg of powder, and by an ultimate process and utility integration even to 2.5 MJ per kg of powder (Walmsley, Atkins, Walmsley, Philipp, & Peesel, 2017).

MVR has a high potential to reduce the energy consumption, but concerns the milk concentration step. The potential for energy recovery from the dryer exhaust air, which contains significant amounts of latent and sensible heat, is not yet fully exploited. Sensible heat recovery from the exhaust has been proposed by Atkins, Walmsley, and Neale (2011) and Golman and Julklang (2014) for spray drying. The application of heat exchangers and proper heat integration resulted in a reduction of the hot utility up to 21% (Atkins et al., 2011). In practice this option is

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still a challenge due to fine powder particles (fines) present in the exhaust air, which cause fouling in the heat exchangers used for heat recovery. Filter systems are needed but result in additional energy loss. Monodisperse droplet atomizers combined with proper airflow patterns and well-designed drying chambers, have the potential to operate without these fines. Both Deventer, Houben, and Koldeweij (2013) and Rogers, Fang, Qi Lin, Selomulya, and Dong Chen (2012) showed that a spray drying system with monodisperse droplet atomizers based on inkjet technology results in a very narrow particle size distribution after drying. Monodisperse droplet drying is now applied at pilot plant scale (Debrauwer, 2016). With successful upscaling this technology reduces the current limitations of sensible heat recovery from the exhaust air and, in combination with air dehumidification, it offers also the possibility for closed–loop drying and latent heat recovery. Dehumidification in closed-loop spray drying, which can recover both sensible and latent heat, is a new instrument for energy saving and will be assessed in this study.

Two technologies are proposed for air dehumidification in combination with closed-loop drying i.e., 1) contact-sorption system with a solid adsorbent (Atuonwu, van Straten, van Deventer, & van Boxtel, 2012), and 2) membrane contactor with a liquid desiccant (brine) (Isetti, Nannei, & Magrini, 1997). Both systems are already proven in other fields, and have potential to be implemented in closed-loop spray drying. Contact-sorption systems use solid adsorbents with a high affinity for water. Zeolite and silica are the most used adsorbents for these systems. Since the spray dryer exhaust air has a temperature in the range of 60 to 90 °C, zeolites are expected to be more effective compared to silica (Boxtel, Boon, Deventer, & Bussmann, 2012). Application of zeolites for air dehumidification in low-temperature dryers has been discussed before, and shows a significant potential for energy savings (Djaeni, van Straten, Bartels, Sanders, & van Boxtel, 2009; Goldsworthy, Alessandrini, & White, 2015). Likewise, zeolites are used for the pre-treatment (dehumidification) of ambient air prior to drying. Advantage of this pre-treatment is the increase in dryer capacity and improved controllability of the dryer conditions (Boxtel et al., 2012). Membrane contactors are currently used for selective separation of gasses (Li & Chen, 2005) and in air conditioning systems (Bergero & Chiari, 2010; Kneifel et al., 2006). In air conditioning systems moist air is separated by a hydrophobic membrane from a saturated brine (i.e. lithium bromide, lithium chloride, magnesium chloride, calcium chloride, or a combination) (Abdel-Salam, Ge, & Simonson, 2013). The partial vapor pressure difference over the membrane is the driving force in these systems, and only water vapor passes through the membrane. Successful applications of membrane contactors for air dehumidification at ambient temperatures are already reported (Isetti et al., 1997; Jain, Tripathi, & Das, 2011; Kneifel et al., 2006), but the potential of these systems for air dehumidification at elevated temperatures has not previously been quantified.

The potential of zeolites and membrane contactors for the dehumidification of the recycled air in spray dryers is investigated in this work. Both dehumidification systems have in common that heat is released when water vapor is adsorbed, and external energy is required for the regeneration of the adsorbent. Air dehumidification is only effective when the heat released at adsorption and the remaining heat from the regeneration are used elsewhere in the system (Atuonwu et al., 2012; Djaeni, Bartels, Sanders, van Straten, & van Boxtel, 2007). This makes heat integration a prerequisite for these proposed configurations to be energy efficient.

Pinch analysis a well-established method for heat integration and the design of heat exchanger networks to minimize external utilities (Kemp, 2007). The pinch approach is a step-wise procedure in which operational conditions, like flows and temperatures, are optimized first. Subsequently, given those optimized conditions, a heat exchanger network is defined according to the pinch rules. The drawback of this approach is the optimized operational conditions are not necessarily the optimal conditions for the heat exchanger network with the minimal external energy requirements. Atuonwu, van Straten, van Deventer, and van Boxtel (2011) applied a simultaneous approach based on the work of Duran and Grossmann (1986), where pinch analysis and optimization of operational conditions were combined in one step. By considering streams and temperatures as variables, the pinch point can be shifted resulting in an additional heat recovery. For a low-temperature drying system with zeolites the simultaneous optimization resulted in a 13% improvement in energy consumption compared to the results obtained with a standard step-wise pinch analysis (Atuonwu et al., 2011). In line with this, Walmsley, Walmsley, Atkins, and Neale (2013) found that applying variable temperatures in pinch analysis for spray drying systems specific heat recovery can be increased by 30%.

Next to the application of the existing methods for the reduction of energy, like multi-stage drying with fluidized bed, air pre-treatment, heat pumps, and heat exchange between inlet and exhaust air, emerging technologies are needed to further reduce the energy consumption in spray drying processes. In this work we discuss the potential for energy reduction by air dehumidification in closed-loop spray drying and compare the results with the common practice in milk powder production. By combining emerging technologies different new closed-loop spray drying configurations are proposed to increase energy efficiency. Simultaneous optimization of the operational conditions and the heat exchanger network is applied to find an optimal process design.

2. Process description

Spray drying systems are intensively used in the dairy industry. Milk powder is, therefore, used as model product. The processing steps for standardized milk powder production are heating, concentrating and drying. The focus in this study is on the dryer section. In the closed-loop spray dryer system a surplus energy stream is created from the regeneration of the adsorbent. To be energy efficient the surplus energy has to be exploited elsewhere in the production process. The surplus of steam is the best used multi-effect evaporators. Mechanical vapor recompression (MVR) systems or combinations of thermal vapor recompression (TVR) with MVR use no or only a minor amount of steam. Therefore a pre-heater and a multi-effect evaporator are included as a heat sink for the surplus energy of the drying process in this work. In Fig. 1, the dryer is given with the loops for air dehumidification, while the pre-heater and multi-effect evaporator are given as two unit operations. The concentrated milk is atomized with a monodisperse nozzle and the spray dryer is operated in closed-loop with air dehumidification. The section for air dehumidification consists of an adsorber (either membrane contactor or zeolite wheel), regenerator, and a cooling/heating unit. The dehumidified air is heated/cooled to the drying temperature before reentering the spray dryer.

The total system is split into subunits, as represented in Fig. 1, and for each subunit overall steady-state mass and energy balances are used:

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

$$H_a = F_a (c_{p,a} + y_a \bullet c_{p,v}) T_a \tag{2}$$

where H is the enthalpy of the flows (kJ h^{-1}), F the mass flow of liquid (l), solids (s) and air (a) (kg h^{-1}), T the temperature of the flows (°C), x_w the water and y_a the vapor content of the flows (kg kg dry air^{-1}), and c_p the heat capacities of water (w) and vapor (v) (kJ kg^{-1} °C^{-1}).

2.1. Evaporator

Milk is first heated up in a pre-heater, and subsequently concentrated in a multi-effect evaporator. The energy requirements for heating follow from Eq. (1), and the size of the heat exchanger (A_{hex}, in m^2) is based on the following equation. In which Q_{hex} is the amount of energy exchanged, U is the heat transfer coefficient, and ΔT the temperature difference.