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Optimizing Energy Efficiency in Low Temperature Drying by Zeolite Adsorption and Process Integration

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Drying is an energy intensive process, with low efficiencies, particularly at low drying temperatures required for heat-sensitive products. This work presents an energy efficient method for drying heat-sensitive products based on drying air dehumidification by zeolites and process integration. Two optimization approaches are considered: sequential and simultaneous. In the sequential approach, a zeolite adsorption dryer is optimized for energy efficiency, subject to product temperature and final moisture constraints using the zeolite, drying and regeneration air flowrates as well as the regeneration air inlet temperature as decision variables. Heat is then optimally recovered from the process exhaust streams using pinch analysis. In the simultaneous method, heat recovery is considered an integral part of the drying process and the entire system simultaneously optimized. Since the heat recovery stream properties are now unknown a priori, the pinch point is not unique but determined by optimization. The sequential and simultaneous methods reduce energy consumption by about 45 % and 55 % respectively, compared to a conventional convective dryer at the same drying temperature of 50 °C.

1. Introduction

Drying is an energy intensive process that accounts for about 15 % of industrial energy consumption, thus contributing significantly to operating costs and environmental impact. For heat-sensitive products (e.g., food and pharmaceuticals), an additional requirement for quality retention is low drying temperatures. At these temperatures however, energy efficiency is low, where energy efficiency η is defined as the ratio of the latent heat of evaporation Q_{evap} of the moisture removed to the total energy input Q_{in}. A common way to improve energy efficiency is heat recovery. For conventional convective dryers, this entails preheating the dryer input air by the exhaust air using heat exchangers (Atkins, et al., 2010). For low temperature dryers, this is thermodynamically infeasible as the exhaust air temperature is too low (close to ambient). Moreover, the exhaust air is usually dust-laden as a result of which, heat exchanger fouling is a major problem that precludes heat integration (Kaiser, et al., 2002). Drying air dehumidification using adsorbents increases the capacity of the air to evaporate water from the product at low drying temperatures. The main energy input is in adsorbent regeneration which typically takes place at high temperatures. This in itself

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presents opportunities for beneficial heat integration as the regenerator exhausts have high energy contents with minimal dusts. As more water is removed during dehumidification, higher sensible heat (due to adsorption heat release) and latent heat carrying capacity (due to moisture loss) are gained. However, more energy has to be spent on regeneration. Using an optimization strategy, it is possible to determine operating conditions that maximize the net energy gains while satisfying constraints on product quality which also is a main performance indicator of any drying process.

In this work, a steady-state model of a zeolite adsorption dryer is optimized for energy efficiency in two ways. In the first approach, the drying process is optimized with respect to operating conditions like zeolite, drying and regeneration air flowrates as well as the regeneration air inlet temperature. Afterwards, the exhaust streams are analysed for heat recovery by pinch analysis. In the second, a "look-ahead" approach is applied where heat integration is anticipated and the system simultaneously optimized for overall efficiency. This creates an additional problem for conventional pinch analysis in that the temperatures and flows of the heat recovery streams are unknown as they depend on the adsorption, regeneration and drying conditions which themselves are within the optimization problem. A pinch point location optimization procedure (Duran and Grossmann, 1986) is used in solving the problem. The possibility of phase change in a hot stream is also considered as in Gundersen et al. (2009).

2. Process Description

The basic adsorption drying process (Figure 1) consists of the dryer, heat source(s) and a zeolite adsorption/regeneration system. Ambient air is dehumidified by passing it through a zeolite bed, gaining adsorption heat H_{ads} in the process, before being used for drying. The spent zeolite is regenerated using hot air obtained by heating ambient air through a heater. The adsorption, regeneration and drying processes are similar in nature as they involve the drying of process air, zeolite and product respectively. As such, they are governed by similar relations and can be represented concisely in the vector form [Dryer Adsorber Regenerator] (Atuonwu et al., 2010). The steady-state mass and energy balances of the system (where each bold-face term is in the vector form) are given by:

$$\mathbf{X_s} = \mathbf{X_e} + \frac{1}{1+\mathbf{k}\boldsymbol{\rho}_\mathbf{s}\mathbf{V_s}/\mathbf{F_s}}\left(\mathbf{X_{sin}} - \mathbf{X_e}\right) \quad (1)$$

$$\mathbf{Y_a} = \frac{\mathbf{F_s}}{F_{aA}}\left(\mathbf{X_{sin}} - \mathbf{X_s}\right) + \mathbf{Y_{ain}} \quad (2)$$

$$\mathbf{T_a} = \frac{F_{aA}\left[\left(C_{pa} + \mathbf{Y_{ain}}C_{pv}\right)\mathbf{T_{ain}} + \left(\Delta H_v + \left(\boldsymbol{\alpha} + \boldsymbol{\beta}\right)H_{ads}\right)\left(\mathbf{Y_{ain}} - \mathbf{Y_a}\right)\right] + \mathbf{F_s}\left[\left(\mathbf{C_{ps}} + \mathbf{X_{sin}}C_{pw}\right)\mathbf{T_{sin}}\right]}{F_{aA}\left(C_{pa} + \mathbf{Y_a}C_{pv}\right) + \mathbf{F_s}\left(\mathbf{C_{ps}} + \mathbf{X_s}C_{pw}\right)} \quad (3)$$

$$\mathbf{T_s} = \mathbf{T_a} \quad (4)$$

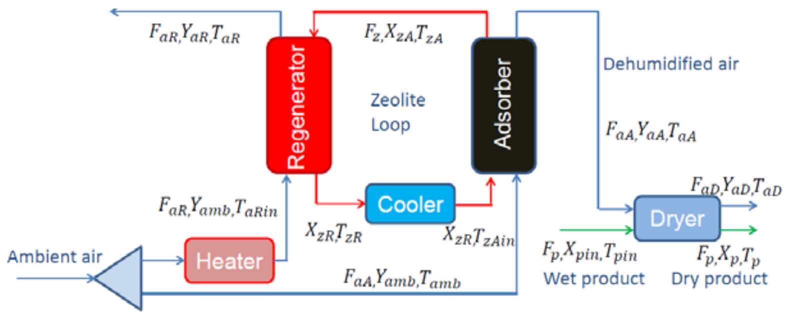

Figure 1: System configuration with adsorption/regeneration realized by rotary wheel.

where each multiplication and division is element-wise and,

$$\begin{bmatrix} \mathbf{X_s} \\ \mathbf{Y_a} \\ \mathbf{T_a} \\ \mathbf{T_s} \end{bmatrix} = \begin{bmatrix} X_p & X_{zA} & X_{zR} \\ Y_{aD} & Y_{aA} & Y_{aR} \\ T_{aD} & T_{aA} & T_{aR} \\ T_p & T_{zA} & T_{zR} \end{bmatrix} \quad (5)$$

Complete details of the model including modeling assumptions, coupling and constitutive relations are available in Atuonwu et al. (2010).

3. Optimization Problem Formulation

3.1 Degree of freedom analysis and general optimization problem

The system of Figure 1 has 10 input variables: product flowrate (dry basis) F_p, inlet moisture content X_{pin}, temperature T_{pin}, ambient air temperature T_{amb}, absolute humidity Y_{amb}, flowrates of drying air F_{aA}, regenerating air F_{aR} and zeolite F_z. Other inputs are the regeneration air inlet temperature T_{aRin}, manipulated by the heater and adsorber zeolite inlet temperature T_{zAin}. For constant feed inlet and environmental conditions, F_p, X_{pin}, T_{pin}, T_{amb} and Y_{amb} are fixed. T_{zAin} is equal to the ambient for which the manipulating cooler is appropriately rated. This leaves 4 degrees of freedom: F_{aA}, F_z, F_{aR} and T_{aRin}. This is physically interpreted as: for every desired product throughput, an optimal air flowrate F_{aA} is required. For this air flowrate, a zeolite flow F_z is required for optimal dehumidification; for which a corresponding regeneration air flow F_{aR} is needed. For all these, an optimal regeneration air temperature T_{aRin} is required to achieve the required regeneration which in turn affects dehumidification and product drying.

The optimization problem is formulated as

$$\text{Maximize}\ \eta\left(F_{aA}, F_z, F_{aR}, T_{aRin}\right) = \frac{Q_{evap}}{Q_{in}} = \frac{F_p\left(X_{pin} - X_{pout}\right)\Delta H_v}{Q_{in}} \quad (6)$$

subject to (1) – (5) as well as product final moisture, maximum temperature and regeneration temperature limits:

$$X_{pout} = 0.05\,, T_{p\max} \leq 50\,, 100 \leq T_{aRin} \leq 400 \quad (7)$$

3.2 Sequential and simultaneous optimization approaches

In the sequential approach, the drying system is first optimized (using equations (1)-(7)) where the energy input is the total spent on heating ambient air to the required regeneration air inlet temperature T_{aRin} given by:

$$Q_{in} = F_{aR}\left(C_{pa} + Y_{amb}C_{pv}\right)\left(T_{aRin} - T_{amb}\right) \tag{8}$$

Given the results of the optimization, the exhaust streams, namely the regenerator outlet air (H1) and zeolite (H2) (whose properties are now known) are taken as hot streams since they exist at high temperatures and need cooling. The ambient air to be heated to regeneration temperature (C1) and the one to the adsorber (C2) are taken as cold streams - Figure 2(a). The problem table method (Kemp, 2007) is used in pinch analysis of the process by shifting all hot stream temperatures downwards by one-half the minimum heat exchanger temperature difference $0.5dT_{min}$, and cold stream temperatures upwards by the same value. Heat exchange is then calculated on each temperature interval. The dotted line in Figure 2(a) represents possible condensation of H1 if it cools below its dew point T_{dptR}. In this region, potential heat exchange is determined as equal to the mass of moisture condensed in the cooling process multiplied by the latent heat of evaporation ΔH_v. The fact that the inlet and target temperatures (points 1, 2, 3 & 4) on the hypothetical pinch diagram Figure 2(b) as well as heat capacity rates are known from the drying process optimization means there is a unique pinch point [p_h p_c].

In the simultaneous approach however, new decision variables arise. The hot stream exhaust and cold stream inlet temperatures (as viewed from the drying process) are now free variables. The co-ordinates of points 1 and 4 on the temperature axis are free to move even though those of points 2 and 3 are fixed. In addition, the flowrates F_{aA}, F_z, F_{aR} and hence, heat capacity rates are decision variables so, the slopes (and hence shapes) of the different portions of the pinch diagram are indeterminate. There is thus no unique pinch point. The pinch point must be determined by optimization. Meanwhile, the co-ordinates and shapes of the pinch diagram interact with the drying process and must be such that the drying requirements are met while the drying process must create stream properties such that the thermodynamic constraints on heat exchange (e.g. dT_{min}) are met. To reduce the search space of possible pinch points, it is assumed that the pinch point occurs at one of the inlet sides of the possible heat exchangers.

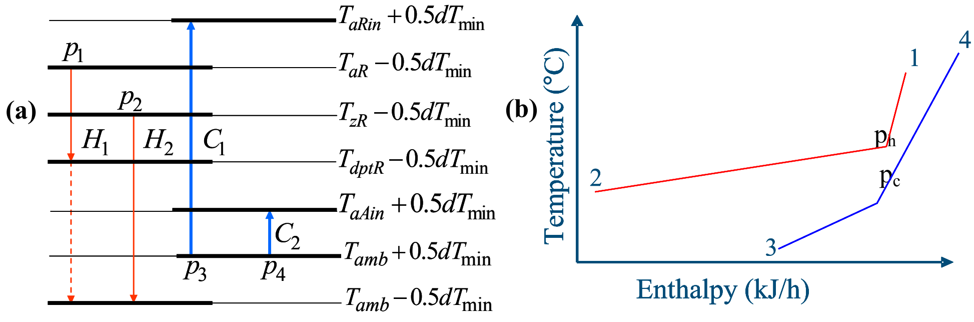

Figure 2: Heat recovery grid (a) and Hypothetical pinch diagram (b)

In Figure 2(a), this represents points p1 (for the regenerator exhaust air), p2 (for the regenerator exhaust zeolite), p3 and p4 (for the ambient air to the regenerator and adsorber respectively). The philosophy behind this assumption is that a cold stream can only heat up until it is limited by the inlet temperature of the hot stream which is on the other side (for a counter-current heat exchanger). The converse is also true. With this assumption, heat balances are written above and below each potential pinch point to establish respectively, minimum external heating and cooling utility required which form extra constraints. The optimal pinch point is that which minimizes overall external heating utility while satisfying drying, thermodynamic and all other constraints.

4. Results and Discussion

The results presented in Table 1 (with decision variables starred *) show that for the same evaporative energy Q_{evap} of 8.995×10^5kJ/h, the sequentially optimized system consumes 14×10^5 kJ/h without heat recovery and 9.18×10^5 kJ/h after heat recovery. This is respectively 20 and 45 % less than the 17.33×10^5 kJ/h consumed by a conventional convective dryer (Figure 3) at the same drying temperature. The simultaneously optimized system consumes 7.96×10^5 kJ/h which represents a 55 % reduction. The conventional dryer does not benefit from adsorption heat release and then, heat integration as the exhaust air temperature is low (36 °C) which for a heat exchanger temperature difference of 10 °C can only heat up the incoming ambient air by 1 °C. It also requires more air flow for the same evaporation. The simultaneously optimized system requires the least drying air flowrate and ensures more dehumidification and better zeolite utilization. The sequentially optimized system requires the maximum temperature (400 °C) for regeneration and hence, less regeneration air flow. Although this favours regeneration and hence, the drying process, it limits heat recovery. As a result, only sensible heat can be recovered via heat exchanger HX1 (Figure 4). In the simultaneous case, the regeneration air flow is raised, reducing the temperature requirement to 265 °C and the exhaust air becomes 188 °C as against 170 °C for the sequential case (as there is much less temperature drop due to the much higher heat capacity rate). The result is much higher sensible heat recovery. Also, the adsorber inlet air is now preheated and latent heat recovered through HX2 after the regenerator outlet air has cooled to 46°C (stream 10) via HX1 and below dewpoint to 38 °C (stream 12).

Table 1: Optimal operating conditions for adsorption and conventional systems

	Sequential			Simultaneous			Conventional		
No.	Flow (kg/h)	Temp. (°C)	Humidity (kg/kg)	Flow (kg/h)	Temp. (°C)	Humidity (kg/kg)	Flow (kg/h)	Temp. (°C)	Humidity (kg/kg)
1	*53000	25	0.01	*50700	28	0.01	70835	25	0.01
2	53000	49	0.0038	50700	49.5	0.0031	70835	49	0.01
3	53000	31.8	0.0106	50700	31.3	0.0101	70835	36	0.0151
6	*4115.2	25	0.0868	*2900	25	0.0403			
7	4115.2	49	0.1664	2900	49.5	0.1611			
8	*3713.4	*400	0.01	*8960	*265	0.01			
9	3713.4	170.4	0.0982	8960	187.6	0.0492			

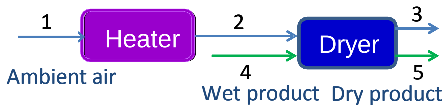

Figure 3: Conventional drying system

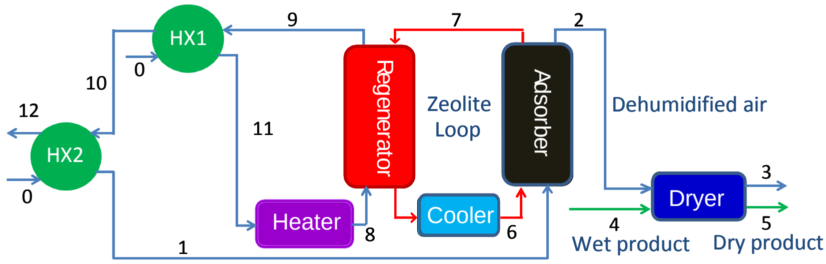

Figure 4: Heat integrated adsorption drying system

5. Conclusion

Adsorption dryers are more energy efficient than conventional dryers at low drying temperatures and provide more heat recovery benefits which are best exploited when the system is simultaneously optimized. Although extra investment costs would be incurred, the increasing energy costs should make for low payback periods while satisfying stringent environmental regulations and of course, product quality demands.

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