Drying Energy Saving by Applying Self-Heat Recuperation Technology to Biomass Drying System

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An advanced energy saving system with air as the drying medium was proposed based on self-heat recuperation technology for the biomass drying in this work. Compared to the previously developed design, the advanced process consumes less energy by considering heat pairing which means the sensible heat is paired with sensible heat and latent heat is paired with the evaporation heat, and then reduces temperature difference between the hot and cold streams in the heat exchanger. The innovitive drying concept was applied to both the co-current dryer (the fluidizied bed dryer) and the counter-current dryer. For the fluidized bed drying system, we introduced a multistage fluidized bed as the evaporator for more energy saving to reduce exergy loss during the drying process. Over 30 % of energy could be reduced compaired to the single-stage fluidized bed dryer. The advanced drying concept was also applied to the counter-currrent heat exchange drying systems which were rotary and screw conveyor dryers in this study. Energy consumption in these new developed drying system is qulifed and compaired through the process simulator. Results shows that energy consumption could be reduced to 1/4-1/6 of a conventional heat-recovery dryer based on our simulation results.

1. Introduction

Biomass is one of the renewable primary energy sources, due to its low net CO_2 emissions and potentially sustainable if the economical, environmental and social impacts are properly managed. Biomass resources show great potential as a sustainable energy, however, suffer the problems of low energy density, and high moisture content that commonly exceeds 50 wt% (wet basis, wb), which limit their applications as an alternate fuel. Biomass densification has been used effectively to deliver bulk and widespread biomass to bioconversion plants, however, consumes a large amount of energy in the biomass pelleting process. An energy audit (Mani et al. 2006) revealed that drying operation in a typical pellet plant using fresh chopped wood feedstock is responsible for 80-82 % of total energy consumption and 85 % total greenhouse gas emissions occurred in a pelleting plant. To reduce energy consumption in the pelleting process, the most effective unit operation to work on is the biomass drying, which currently is commonly carried out in rotary dryers of single or multiple passes without energy recovery or recuperation from exhaust gases. Energy-saving dryers have been developed; however, conventional energy-saving dryers can only recover 20-30 % heat (Linnhoff and Hindmarsh 1983). Thus, it is crucial to explore a high energy-efficient drying process.

To improve the energy efficiency in the drying process, Aziz et. al (2011) have recently developed an energy-saving biomass drying process based on self-heat recuperation (SHR) technology. The exergy rate of the hot stream is elevated by compression to provide a minimum temperature difference

required for heat exchange with the cold stream. As a result, all of the heat involved in drying can be recuperated and reused as a heat source for the subsequent drying process. This includes recuperation of sensible heat from the gas serving as the drying medium and the dried products, both sensible and latent heat of the evaporated water. The results showed an up to 75 % energy-saving potential could be achieved, compared to a conventional dryer without heat recuperation based on process simulation. However, based on our calculation results, energy consumption was still much higher compared to the theoretical minimum input energy for the drying process (Liu et al. 2012). In addition, until now, SHR technology has only been applied to the fluidized bed dryer. It is known that, there are other drying systems such as the rotary dryer, screw conveyor dryer, and fixed bed and moving bed dryers for the biomass drying. However, no investigation about SHR technology applied to the above drying systems has been conducted. Therefore, it is necessary to verify the energy saving potential by applying SHR technology to other drying systems and widen the application of SHR technology to other biomass drying systems.

In the current work, we introduced an advanced drying process based on SHR technology to facilitate an optimal heat exchange and for further exergy recuperation. The objective of this work is to evaluate the energy saving potential by applying the advanced SHR technology to the drying systems including both the co-current heat exchanger (the fluidized bed) and counter-current heat exchanger (the rotary and screw conveyor dryers). In the beginning, the concept of the advanced drying process was described in detail. Then, based on this concept, we developed a multistage fluidized bed dryer and energy consumption was investigated. Furthermore, we investigated energy saving potential by applying SHR technology to the co-current heat exchange drying systems such as rotary dryer and screw conveyor dryer. Finally, energy consumption in each drying system was calculated and compared, and reasons for energy saving in each drying system were discussed.

2. Drying process based on self-heat recuperation technology

Figure 1a shows the basic schematic of layout of the exergy recuperative drying process for biomass drying. Compared to the former drying concept developed by Aziz et al. (2011), this advanced drying process focuses to perform heat pairing for each sensible and latent to reach optimal heat recuperation. The advanced drying process can be divided into two continuous stages: preheating and evaporation. Biomass particles enter heat exchangers (HX1-HX4) for pre-heating to a certain temperature. HX1, HX2 and HX3 are heat exchangers for recycling the sensible heat of condensed water, dried biomass and hot air, respectively. The sensible heat of the air-steam mixture is removed for preheating the wet biomass (HX4). Energy provided by the hot streams is equal to the required sensible heat for biomass drying. Subsequently, preheated biomass enters the second stage—evaporator (HX5 and separator) where the water in the biomass is evaporated. For the fluidized bed dryer, HX5 stands for the multistage fluidized bed dryer, and for the rotary and screw conveyor dryers, HX5 stands for a counter-current heat exchanger. The air-steam mixture from the evaporator is compressed, and then circulated back and utilized as heat source for evaporation and pre-heating of the raw biomass. In this drying system, the drying medium can be recirculated resulting in a broader possibility of application of any inert gas such as nitrogen, carbon dioxide, etc. to avoid a spontaneous combustion during drying. Moreover, energy and material flow diagram of the advanced drying process is provided in Figure 1b. The boxes represent units, and the lines represent the flow of materials or energy. The material flow in the diagrams comprises the flow of air, (dry) biomass and water, and wet biomass is considered as combined (dry) biomass and water. We assumed that a heat exchanger (HX) can be divided into a self-heat transmitter (HT) and a self-heat receiver (HR). No external heater is required in the SHR dryers. Total required energy input for the biomass drying includes: the heat transferred to biomass in the preheating period and the heat transferred to biomass in the evaporation (no bound water is evaporated) which could be calculated through Equations 1 and 2.

$$H_{sensible} = V\rho_a C_p (T_0 - T_1) = W(C_d + m_0 C_m)(t_1 - t_0) \tag{1}$$

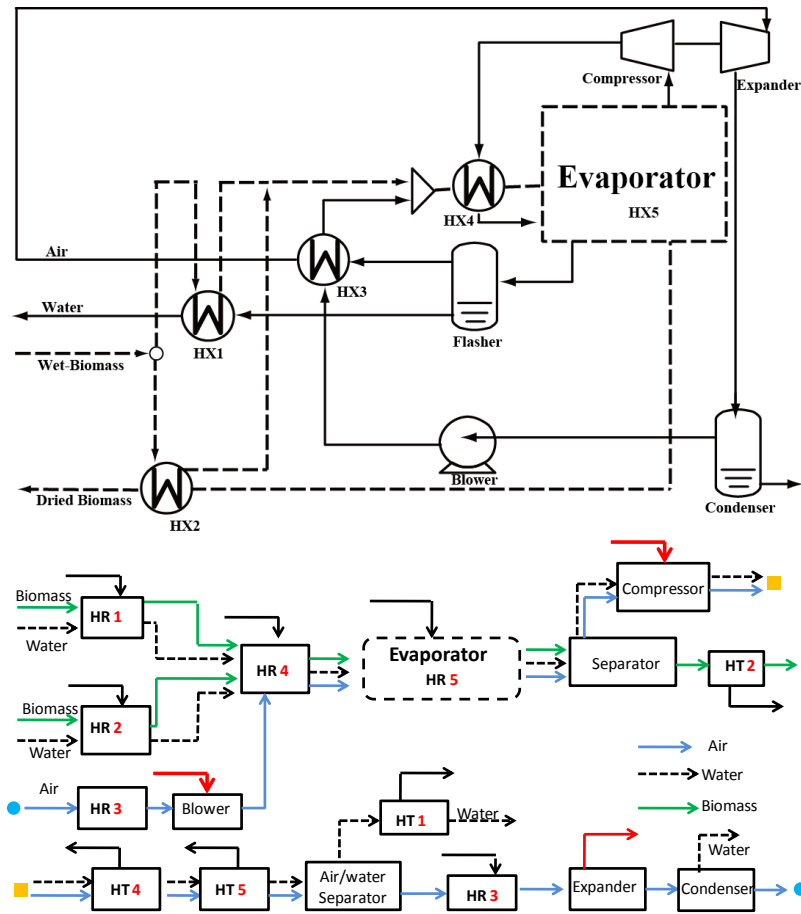$$H_{latent} = H_{vap} W(m_0 - m_2) \tag{2}$$

Figure 1: a.Schematic drying system of advanced drying process; b.Energy and materials flow diagram of the advanced drying process.

3. Process simulation and calculation of energy consumption

Three drying systems were studied based on the advanced SHR technology: the fluidized bed dryer and the rotary and screw conveyor dryers. To evaluate energy efficiencies of different drying systems, the mass and energy balance was calculated using Pro/II ver. 9.0 software (Invensys Corp.). The biomass inlet flow rate is 10 t h^{-1} with an initial moisture content of 50 wt% (wb). Drying is conducted until a moisture content of 20 wt% (wb) is reached. The adiabatic efficiencies of the compressor, blower and expander are 80%, 80% and 90%. Drying is performed under atmospheric conditions. Thermodynamic calculations employ the Soave–Redlich–Kwong method. The heat exchange is co-current in the fluidized bed dryer and counter-current in other heat exchangers. The minimum temperatures in the fluidized bed dryer and other heat exchangers approach 10 and 30 K, respectively. The flow direction of biomass with respect to air in each drying system is co-current flow which has higher drying rate compared to the counter-current flow (Waje et al. 2006).

To verify energy-saving potential by applying SHR technology to the drying system, energy input in each drying system was qualified and compared. In the fluidized bed dryer, energy consumption mainly comes from the blower to compensate pressure loss in the fluidized bed. In the rotary dryer, energy is consumed due to pressure loss in the dryer and power of the motor to drive the rotary dryer, and in the screw conveyor dryer, energy is consumed for turning the screw and moving the materials. Equations for the calculation of energy consumption in the each drying system are available in Table 1.

Table 1. Pressure loss in the drying system and mechanical power input for the motor of the dryer.

Fluidized bed dryer	Rotary dryer	Screw conveyor dryer
Pressure loss in the dryer $\Delta p_f = \Delta p_b + \Delta p_d$ $\Delta p_b = (1 - \varepsilon_{mf})(\rho_p - \rho_g)H_b \dfrac{g}{c}$ $\Delta p_d = 0.4 \Delta p_b$ $U_{mf} = \dfrac{d_{peff}^2 (\rho_{eff} - \rho_g) g}{1650 \mu_g}$ $\rho_{eff} = k \dfrac{w_1 p_1 + w_2 p_2}{w_1 + w_2}$ $d_{peff}^2 = k \left[dp1 \left[\left(\dfrac{\rho_1}{\rho_2} \right) \left(\dfrac{\rho_1}{\rho_2} \right)^{w2/w1} \right] \right]^2$ $k = 20 d_{p1} + 0.36$	Pressure loss in the dryer $\Delta P_s = \left[4f(N_b + 1)D_s G_s^2 \Big/ 2D_e \rho_{vap} \right] \times 0.5$ $D_e = \left[\dfrac{P_T}{2} \times 0.86 \times P_T - \dfrac{1}{2} \left(\dfrac{\Pi D_0^2}{4} \right) \Big/ \dfrac{\Pi D_0}{2} \right]$ Duty of motor $bhp = \dfrac{N \left[4.75Dw + 0.1925(D+2)W + 0.33W \right]}{100,000}$ $V = \dfrac{\tau F_2}{H \rho_s}$ $W = F\tau$ $W = w + W_{equip}$	Duty of motor $P_{power} = P_{screw} + P_{material}$ $P_{screw} = 0.1 LNF_D F_B$ $P_{material} = 5.5 \times 10^{-3} LC \rho F_M F_f F_P$ $C = \alpha \dfrac{\pi}{4} \left([D_{sc} + 2r]^2 - D_{sh}^2 \right)(P - t) N \times 60$

4. Results and discussion

4.1 Energy consumption in the single-stage and multistage fluidized bed dryers

The main characteristic of heat circulation technology is the exergy recuperation through compression and optimal heat pairing for each sensible and latent heat (Kansha et al. 2009). In the former drying process proposed by Aziz et al, the largest exergy loss occurs in the fluidized bed dryer of the drying system due to unmatched heat pairing in the overall drying system which is shown in Figure 2a. The reason is that a large amount of sensible heat of air generated during the compression process causing the unmatched heat pairing (Figure 2a). Some part of sensible heat of the compressed air-steam mixture is paired with the evaporation heat causing part of the latent heat paired with sensible heat. The irreversibility of heating would be minimal when the heat to the feed stream is supplied from the heat source, which has the same heat capacity and the temperature different at any point in the heat exchanger will be equal to the ΔT_{min}. However, the temperature difference increased due to the different heat capacities between the biomass and the compressed steam due to the unmatched heat pairing and then causes a high temperature difference in each heat exchanger. Therefore, a large amount of energy input for the compressor was required to provide a high temperature difference between the biomass and the air-steam mixture. The additional heat will be thrown as the form of a high temperature of condensed water and dried biomass based on the energy balance. On the other side, the temperature difference between the hot and cold streams in the fluidized bed dryer was much larger than the ΔT_{min} in the fluidized bed dryer. Further energy saving can be predicted if the temperature difference between the hot and cold streams is decreased near to the ΔT_{min} in the fluidized bed evaporator, thus diminish the irreversibility. To reduce the energy consumption, in this work, we tried to increase the stage number of the fluidized bed by decreasing the temperature difference near to the ΔT_{min} in the heat exchanger. More stages can be predicted near to the ΔT_{min} (Holmberg and Ahtila 2005) to reduce energy consumption, however, the increased pressure loss due to increasing number of stages will also increase duty of the blower. Therefore, based on our investigation, we chose a three-stage of fluidized bed considering balancing the energy consumption due to the pressure loss and the temperature difference decrease by increasing the stages of the fluidized bed.

Temperature-enthalpy diagrams of Figure 2a and 2b have the same heat input ($Q_{sensible} + Q_{latent}$). While, Figure 2b shows a better heat paring for each sensible and latent heat which means less energy is needed for the drying process. Energy consumption of the drying processes, calculated based on the simulation results from Pro/II software, are presented in Table 2. More than 30 % energy can be saved in the advanced drying process compared to the previous drying process. Moreover, in the advanced drying system, the temperature of the air-steam mixture (220 °C) was much lower than that in the previous drying system (340 °C) which avoided the deterioration of the biomass quality due to the high temperature.
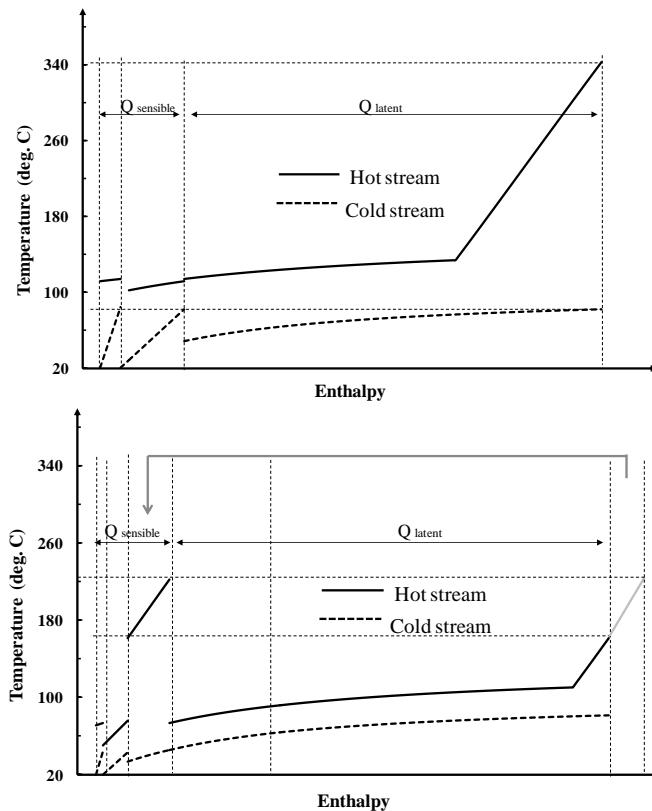
Figure 2: a. Temperature-enthalpy diagram for the biomass drying system from Aziz; b. Temperature-enthalpy diagram for the advanced biomass drying system.

4.2. Energy saving potential in the counter-current heat exchange dryer

Table 2 illustrates that energy consumption in this new developed drying system could be reduced to 1/4-1/6 of a conventional heat-recovery dryer. The value varies with the amount of air input in the drying systems. More energy could be saved in the rotary and screw conveyor dryers than the fluidized bed dryer, mainly owing to:

1) The less air amount required in the rotary and screw conveyor dryers compared to that in the fluidized bed dryer. In the rotary dryer, biomass particles are moved through the dryer due to gravity from the slop of the drum and drag of the gas. In the screw conveyor dryer, particles are mainly moved by the screw. However, in the fluidized bed dryer, a large amount of air with high velocity is required to compensate the pressure loss in the fluidized bed causing a high power input for the blower. Energy consumption based on SHR technology mainly comes from the compressor and large mount of input air would increase the energy input for the compressor and generate a large amount of sensible heat of air causing the unmatched of heat pairing. Also, high ratio of air to produce requires more energy for the separation of air from the air-steam mixture increasing the overall energy input.

2) Temperature difference between the cold and hot streams is near to ΔT_{min} in the counter-current heat exchange dryer than the co-current heat exchange dryer, which increases the energy efficiency.

The screw conveyor dryer shows the most energy-saving potential which requires less air and power for the motor. However, the main drawback of the screw conveyor dryer is the requirement of a long length dryer due to the low heat transfer rate which is commonly below 70 W/m^{2}K. Although more energy consumption in the fluidized bed, the gas-solid surface which increases heat and mass transfer rates and decreases the drying time and surface area of the heat exchanger. The relationship between the energy saving and drying rate in the drying system is required to be studied in the future study.

Table 2. Energy consumption in each drying system. ([a]CHR: conventional heat-recovery dryer, FBD: fluidized bed dryer,SCD: screw conveyor dryer. [b]Negative values mean recuperated work. Energy consumption for 10t/h raw biomass drying from 50 wt% (wb) to 20 wt% (wb) in each drying system.)

Dryer type	CHR	Single-stage FBD			Multistage FBD			Rotary dryer			SCD
Air flow (t/h)		6.2	12.4	18.6	6.2	12.4	18.6	1.0	3.1	6.2	1.0
Energy Input (kW)											
Heater	2700	-	-	-	-	-	-	-	-	-	-
Blower	-	48	92	135	95	185	276	4	13	25	-
Compressor	-	1103	1383	1682	529	692	854	375	467	575	375
Expander	-	-303	-551	-744	-157	-270	-372	-39	-95	-169	-39
Motor	-	-	-	-	-	-	-	98	98	98	60
Total input	2700	748	939	1074	449	590	726	428	483	529	396

5. Conclusions

In this paper, an innovative design methodology of biomass drying by using self-heat recuperation technology has been proposed to reduce the energy consumption. Three drying systems (fluidized bed dryer, rotary dryer and screw conveyor dryer) were investigated based on self-heat recuperation technology. Energy consumption can be reduced to 1/6-1/4 of a conventional heat-recovery dryer by considering heat pairing in the new developed drying system and reducing the temperature difference near to ΔT_{min} in the heat exchanger. Energy saving by applying self-heat recuperation technology to the drying systems mainly depends on the counter/co-current heat exchange and the temperature difference between the hot and cold streams in the main heat exchanger. Moreover, higher air to product ratios could make the heat pairing shift and cause part of energy unrecycled. This study shows that SHR technology is a promising energy-saving technology to be applied to the biomass drying industry.

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