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Improving Energy Efficiency of Cogeneration System in Cane Sugar Industry by Steam Dryer

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Cogeneration system in the cane sugar industry produces not only molasses and raw sugar but also exportable electrical power. Main components of the system are boiler, steam turbine, condenser, and sugar juice evaporation process. Bagasse is used as fuel for boiler. Bagasse is a by-product of sugar juice extraction process. It is characterized by a high moisture content, which leads to the inefficiency of energy conversion. The integration of steam dryer in cogeneration system to reduce bagasse moisture content before combustion will improve the system performance. The moisture content of bagasse is reduced in a steam dryer due to heat transfer from steam condensation. Saturated steam supplied to steam dryer is obtained by mixing superheated steam extracted from steam turbine with the appropriate amount of cooling water in desuper-heater. The objective of this paper is to evaluate the performance of this cogeneration system quantitatively. Models of boiler and steam dryer are used for this purpose. Simulation results show that the cogeneration system integrated with steam dryer generates more power output than the reference cogeneration system without steam dryer under the conditions that sugar juice processing capacity and bagasse consumption are the same. Furthermore, the cogeneration system integrated with steam dryer requires 20% less heating surface area than the reference cogeneration system under the condition that temperatures of flue gas exhausted from boilers of both systems are the same.

1. Introduction

Main components of cogeneration system in cane sugar industry are boiler, steam turbine, condenser, and evaporation process. Boiler generates high-pressure steam that is expanded in condensing-extraction steam turbine. Steam extracted from the turbine provides thermal energy to convert sugar juice into raw sugar and molasses in evaporation process. There have been several suggestions for improving energy efficiency of this cogeneration system. Birru et al. (2019) showed that modifications of cogeneration system in sugar mills could increase cogeneration efficiency. Diaz Perez et al. (2018) determined the optimum installations of reheater and regenerative feed water heaters in cogeneration systems of Brazilian sugar and ethanol sector. Ensinas et al. (2007) determined the optimum distribution of heat exchanger surfaces that minimized steam use in sugar juice evaporation system using a thermo-economic procedure. Deshmukh et al. (2013) recommended using biomass integrated gasifier combined cycle. Alves et al. (2015) showed that using extraction-condensing turbine in a cogeneration system resulted in larger surplus electrical power generation than using back-pressure turbine. Burin et al. (2015) investigated the use of concentrated solar power in cogeneration system to improve system performance. Dogbe et al. (2019) demonstrated that the integration of organic Rankine cycle for waste-heat recovery led to both increasing energy efficiency and exergy efficiency. Singh (2019) proposed using waste heat in high-temperature flue gas from boiler to operate vapor absorption refrigeration system.

Sugar factories use bagasse as fuel for boilers. Bagasse is a by-product of raw sugar manufacturing process. It is usually characterized by a high moisture content. Since boiler efficiency increases with decreasing bagasse moisture content, bagasse drying may be used to improve the performance of cogeneration system. High-temperature flue gas provides a source of energy for bagasse drying. However, boilers in sugar factories are equipped with economizers and air heaters to recover energy from hot flue gas before it is exhausted to the environment, which results in low exhaust flue gas temperature that may not be suitable to be used as a drying agent.

Steam is an alternative source of energy for bagasse drying. Steam extracted from steam turbine at a suitable pressure is supplied to steam dryer. Steam condensation in steam dryer releases thermal energy that is transferred to bagasse, which results in moisture removal. There have been investigations of using steam dryer in biomass-fired cogeneration systems and power plants. Li et al. (2012) compared flue gas drying and steam drying in biomass power plant that used pine chips as fuel. Luk et al. (2013) and Gebreegziabher et al. (2014) proposed the integration of both air dryer and steam dryer in small power plants that used empty fruit bunches as fuel. Liu et al. (2017) performed thermodynamic and economic analyses of the integration of steam dryer in biomass power plant, and found that the cost of steam dryer should be lower than an upper limit to justify its integration. An analysis by Motta et al. (2020) indicates that superheated steam may be more suitable than flue gas for bagasse drying. However, the investigation of the integration of steam dryer into cogeneration system in cane sugar industry has not been carried out yet. Therefore, the main objective of this paper is to perform an analysis of cogeneration system integrated with steam dryer in comparison with reference cogeneration system without steam dryer. Both systems operate under the same conditions so that differences in their performances can be attributed to the integration of steam dryer.

2. Cogeneration system

Raw sugar manufacturing is illustrated in Fig. 1. Inputs to the juice extraction process are 125 ton/h of sugar cane and 50 ton/h of imbibition water. Sugar cane consists of 19.2% fiber, 15.2% dissolved solids, and 65.6% water. It may be assumed that there is no fiber in the extracted juice, and all dissolved solids in sugar cane are transferred to the juice. If bagasse moisture content is 52%, the outputs will be 50 ton/h of bagasse and 125 ton/h of sugar juice, in which the concentration of dissolved solids is 15.2%. In order to produce raw sugar and molasses, 105 ton/h of water must be removed from the diluted juice. According to the analysis by Chantasiriwan (2017), the ratio of the amount of water content removed from the juice to the amount of saturated steam required for the evaporation process depends on the heating surfaces in the process. For this study, this ratio is assumed to be 3. Therefore, the required mass flow rate of saturated steam is 35 ton/h.

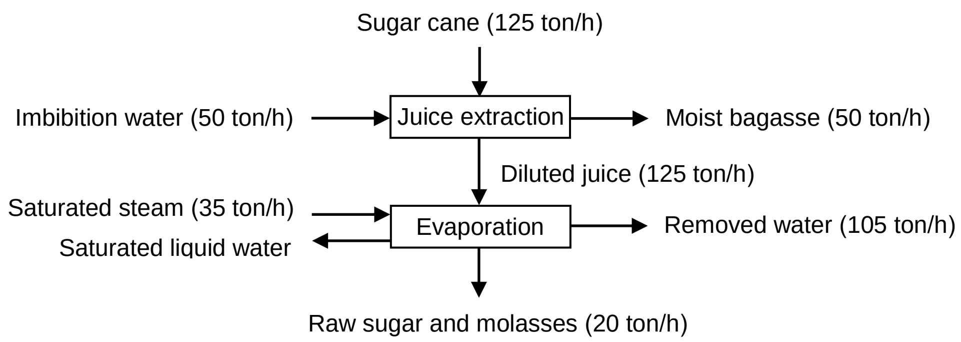

Figure 1: Mass balances in raw sugar manufacturing process.

Figure 2 illustrates the proposed integration of steam dryer in cogeneration system. Solid lines denote flows of steam, dashed lines denote flows of liquid water, and dotted lines denote flows of fuel and air. Combustion of bagasse in boiler (B) provides thermal energy for converting feed water to superheated steam. The mass flow rate, pressure, and temperature of steam are, respectively, m_s, p_s and T_s. The mass flow rate of bagasse is m_f. The dry-basis moisture content of bagasse at the inlet of steam dryer (SD) is y_{Mi}. The inlet bagasse temperature is the same as the ambient air temperature (T_a). Condensing-extraction steam turbine (ST) is used in this system. The pressure of condensed steam is p_c, and the pressure of extracted steam is p_e. This extracted steam pressure is the same as the steam pressure required for the operation of evaporation process (EP). Since extracted steam temperature (T_e) is larger than saturated steam temperature (T_v), extracted steam must be mixed with cooling water from condenser (C) in desuperheater (DS). The resulting saturated steam is sent to evaporation process and steam dryer. Steam dryer reduces the dry-basis moisture content of bagasse from y_{Mi} to y_M, and increases bagasse temperature from T_a to T_f. Saturated liquid water at outlets of evaporation process and steam dyer is pumped to boiler.

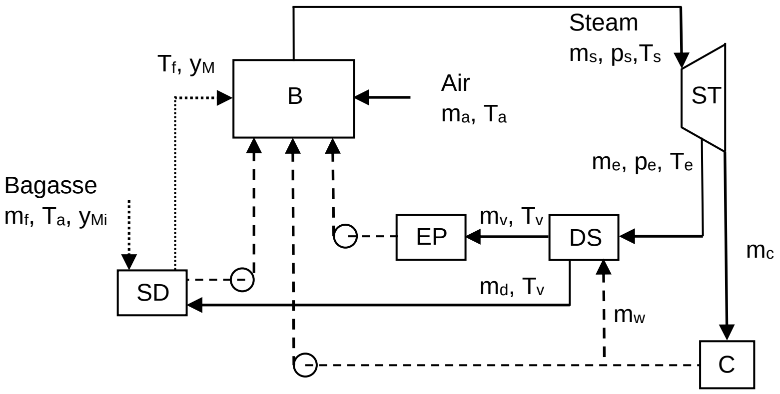

Figure 2: Cogeneration system in cane sugar industry.

3. Models of system components

3.1 Boiler

Boilers used in sugar factories are industrial boilers. An industrial boiler consists of furnace, evaporator, steam drum, superheater, boiler bank, economizer, and air heater. The recent model of industrial boiler presented by Chantasiriwan (2019) is used for simulation in this paper.

3.2 Steam turbine

The type of steam turbine in the cogeneration system is condensing-extraction steam turbine. Steam expansion in steam turbine results in pressure decrease and power output. The power output (P) of steam turbine can be determined if turbine efficiency (η_t) is known. It is expressed as

$$P = m_s \eta_t (h_s - h_{es}) + (m_s - m_e)(h_s - h_{cs}) \quad (1)$$

where h_s is steam enthalpy at turbine inlet, h_{es} is steam enthalpy at pressure p_e and the same entropy as the inlet steam, and h_{cs} is steam enthalpy at pressure p_c and the same entropy as the inlet steam.

3.3 Desuperheater

Evaporation process requires saturated steam. However, the temperature of extracted steam (T_e) is larger than the saturation temperature (T_v). Saturated steam with the mass flow rate of m_v required by evaporation process is provided by desuperheater, in which extracted steam is mixed with cooling water. The mass flow rate of cooling water (m_w) is determined from mass and energy balances of desuperheater:

$$m_w = m_v \left(\frac{h_e - h_v}{h_e - h_c} \right) \quad (2)$$

where h_e, h_v, and h_c are enthalpies of extracted steam, saturated steam, and cooling water.

3.4 Evaporation process

The mass flow rate of saturated steam produced by desuperheater is $m_s + m_w$. Since the mass flow rate of steam delivered to steam dryer is m_d, the mass flow rate of saturated steam sent to evaporation process is

$$m_v = m_s + m_w - m_d \quad (3)$$

Complete condensation of saturated steam occurs in evaporation process. Therefore, the output this process is saturated liquid water.

3.5 Steam dryer

The model of steam dryer is shown in Fig. 3. Saturated steam with the mass flow rate of m_d from desuper-heater is supplied to steam dryer. Steam condensation in steam dryer results in the removal of some moisture in bagasse. Bagasse consists of dry fibrous material and moisture. The mass flow rate of dry fibrous material (m_{fd}), which equals $m_f/(1 + y_{Mi})$, is unchanged throughout the drying process. Bagasse is divided into two portions with mass fractions z and 1 – z. The dry-basis moisture content of the first portion is reduced from y_{Mi} to the design value of bagasse moisture content at dryer outlet (y_{Md}), which is assumed to be 0.5. Energy balance is used to determine z as follows.

$$z = \frac{(m_c + m_d)\Delta h_{vl}}{m_{fd}\left[(c_{pf} + y_{Mi}c_{pw})(T_{sat} - T_a) + (y_{Mi} - y_{Md})\Delta h_{fg}\right]} \quad (4)$$

where c_{pw} and c_{pf} are specific heat capacities of water and dry fibrous material in bagasse, T_{sat} is the saturation temperature at the atmospheric pressure, Δh_{vl} is latent heat of condensation at p_e, and Δh_{fg} is latent heat of evaporation at atmospheric pressure. Before being fed to the boiler, saturated vapor is separated from bagasse in the first portion, and both portions are mixed. The dry-basis moisture content and the temperature of the mixture are determined from mass and energy balances.

$$y_M = z y_{Md} + (1 - z) y_{Mi} \quad (5)$$

$$T_f = \frac{z(c_{pf} + y_{Md}c_{pw})T_{sat} + (1 - z)(c_{pf} + y_{Mi}c_{pw})T_a}{c_{pf} + y_M c_{pw}} \quad (6)$$

Steam dryer cost is assumed to depend on the rate of fuel moisture removal (M) in kg/h, which is expressed as

$$M = 3600 z (y_{Mi} - y_{Md}) m_{fd} \quad (7)$$

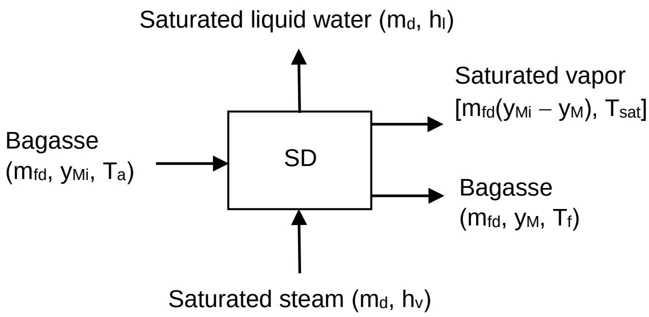

Figure 3: Steam dryer.

4. Results and discussion

According to Rein (2017), dry fibrous material in bagasse consists of 45.92% carbon, 43.89% oxygen, 5.67% hydrogen, 0.31% nitrogen, 0.04% sulphur, and 4.17% of ash. The wet-basis moisture content of bagasse is 52%. The corresponding dry-basis moisture content (y_{Mi}) is 1.083. Parameters of the cogeneration system are p_s = 4.5 MPa, p_e = 200 kPa, p_c = 10 kPa, T_a = 30°C, and η_t = 80%. According to Fig. 1, the mass flow rate of saturated steam in evaporation process (m_v) is 35 ton/h, and the mass flow rate of bagasse from extraction process is 50 ton/h. It is assumed that half of the bagasse is used as fuel, and the other half is reserved for other uses. Therefore, the fuel consumption rate (m_f) is 25 ton/h.

The energy efficiency of the cogeneration system depends on the temperature of flue gas at boiler exhaust. This temperature cannot be too low in order to avoid cold-end corrosion in air heater. It is assumed that the lower limit of exhaust flue gas temperature is 120°C. If other heating surface areas of the boiler are unchanged, exhaust flue gas temperature is a function of air heater surface area. The simulation reveals that, for the cogeneration system without steam dryer, the air heater surface area corresponding to the exhaust flue gas temperature of 120°C is 1252 m^2. The power output of the system is 10.0 MW.

For the cogeneration system integrated with steam dryer, the system performance depends on the mass flow rate of steam in steam dryer. If this mass flow rate is 1 kg/s, the moisture content of bagasse will be reduced from 52% to 46.3% at dryer outlet. The corresponding moisture removal rate in steam dryer will be 2667 kg/h. The air heater surface area of 1252 m^2 in this system will result in the exhaust flue gas temperature of 114.8°C, which is less than the lower limit. The air heater surface area must be reduced to 1045 m^2 in order for the exhaust flue gas temperature to be 120°C. The power output of the system is 10.5 MW. Therefore, the cogeneration system integrated with steam dryer produces 5% more power output, and requires 20% less air heater surface area than the cogeneration system without steam dryer that operate in the same conditions. With increasing mass flow rate of steam in steam dryer, the resulting wet-basis moisture content of bagasse decreases, the moisture removal rate in steam dryer increase, air heater surface area decreases, and power output increases. Since steam dryer is designed to reduce dry-basis moisture content to 50%, the maximum mass flow rate of saturated steam in steam dryer is 2.62 kg/s. Figure 4 shows variations of the wet-basis moisture content of bagasse at dryer outlet and the corresponding moisture removal rate with the mass flow rate of saturated steam in steam dryer. Figure 5 shows variations of air heater surface area and power output with the mass flow rate of saturated steam in steam dryer.

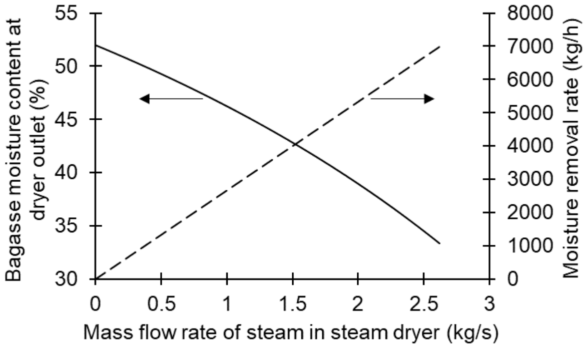

Figure 4: Variations of bagasse moisture content at dyer outlet and moisture removal rate with mass flow rate of steam in steam dryer.

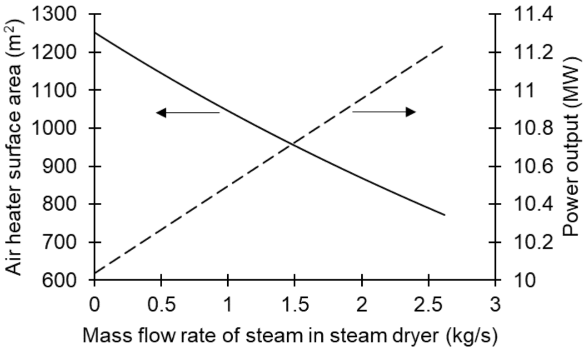

Figure 5: Variations of air heater surface area and power output with mass flow rate of steam in steam dryer.

In order to assess the advantage of the integration of steam dryer in cogeneration system, it is instructive to perform an economic analysis. Let the mass flow rate of saturated steam in steam dryer be 1 kg/s. Assume that the unit cost of steam dryer is 100 \$/(kg/h). The installation cost of steam dryer is \$266,700. The cogeneration system integrated with steam dryer requires 207 m^2 less air heater surface area than the cogeneration system without steam dryer. Assume that the unit cost of air heater is 100 \$/m^2. The total installation cost of the cogeneration system integrated with steam dryer is, therefore, \$246,000 more than that of the reference cogeneration system without steam dryer. The integration of steam dryer results in 500 kW more power output. If the efficiency of the conversion from mechanical power to electrical power is 100%, this number can be converted to 1,440,000 kW.h of electrical energy under the assumption that the annual operation period of the cane sugar factory is 4 months. It can be seen that the gain in electrical energy output outweighs the additional installation cost required for the integration of steam dryer.

5. Conclusions

The integration of steam dryer into cogeneration system in cane sugar industry is proposed and analyzed in this paper. Extracted steam from steam turbine is mixed with cooling water in desuperheater. The resulting saturated steam is supplied to both evaporation process and steam dryer. Thermal energy from steam condensation in steam dryer is transferred to moist bagasse, and results moisture removal. Models of cogeneration system and steam dryer are used to demonstrate that the integration of steam dryer increases the energy efficiency of the system under the same operating conditions. Simulation results show that the reference cogeneration system without steam dryer requiring 35 ton/h of saturated steam for the evaporation process and consuming 25 ton/h of bagasse is capable of generating 10.0 MW of power output. With the supply of 1 kg/s of saturated steam to steam dryer, the cogeneration system integrated with steam dryer produces 5% more power output, and requires 20% less air heater surface area. The gain in power output due to this integration appears to outweigh the additional installation cost required for this integration.

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