International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok, Thailand
Paper ID: 0283

Integration of Parabolic Trough Collector and Steam Dryer in Cogeneration System of Sugar Industry

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ABSTRACT

Cogeneration system in the cane sugar industry consists of boiler, steam turbine, and evaporation process. Bagasse is used as fuel in boiler. Bagasse has 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 will improve the system performance. The use of parabolic trough collector to generate additional steam for steam dryer will enhance the capacity of steam dryer. In the paper, the cogeneration system integrated with steam dyer and parabolic trough collector is proposed. Simulation results from models of cogeneration system, boiler, steam dryer, and parabolic trough collector show that this system is capable of generating more power output than the cogeneration system without steam dyer and parabolic trough collector that consumes the same amount of fuel. The estimation of the payback period for the investment in steam dyer and parabolic trough collector is also provided.

Keywords: Cogeneration, Renewable energy, Biomass drying, Solar-aided power generation

1. INTRODUCTION

The main components of cogeneration system are boiler, steam turbine, and evaporation process. Boiler generates high-pressure steam that is expanded in back-pressure steam turbine. Steam exhausted from the turbine provides thermal energy to convert sugar juice into raw sugar and molasses in evaporation process. 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.

Recently, Chantasiriwan and Charoenvai [1] used a model of cogeneration system integrated with superheated steam dryer in sugar factory to show that superheated steam drying resulted in both decreasing bagasse consumption and increasing power generation efficiency. Chantasiriwan and Charoenvai [2] demonstrated that the integration of both parabolic trough collector and superheated steam dryer led to improved system performance. Superheated steam drying, however, presents technical difficulties because steam and bagasse must be mixed at the same pressure. Bagasse drying in steam dryer is more attractive because steam and bagasse do not come into contact [3]. Heat transfer from steam condensation is transferred through steam tube walls of steam dryer to moist bagasse, which results in moisture removal.

The use of parabolic trough collector to increase power output in cogeneration system of sugar industry by increasing feed water temperature was previously proposed by Burin et al. [4]. However, no previous investigations have considered using parabolic trough collector to enhance steam dryer performance. Therefore, the cogeneration system integrated with steam dyer and parabolic trough collector is proposed in this paper. It is shown that power output of this cogeneration system is more than that of cogeneration system without parabolic trough collector and steam dryer under the same conditions. The gain in power output is then compared with the cost of this integration.

2. SYSTEM DESCRIPTION

Figure 1 illustrates the proposed integration of parabolic trough collector and steam dryer in cogeneration system. Combustion of bagasse in boiler (B) provides thermal energy for producing superheated steam from feed water. 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). 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. Back-pressure steam turbine (ST) is used in this system. The pressure of exhaust steam is p_e. This pressure is the same as the steam pressure required for the operation of evaporation process (EP). Mixing of exhaust steam and cooling water occurs in desuperheater (DS). The resulting saturated steam is sent to evaporation process and steam dryer. Saturated liquid water at outlets of evaporation process and steam dyer is pumped to boiler. Additional saturated steam supplied to steam dyer comes from parabolic trough collector (PTC). The same amount of saturated liquid water leaving steam dryer is returned to parabolic trough collector.

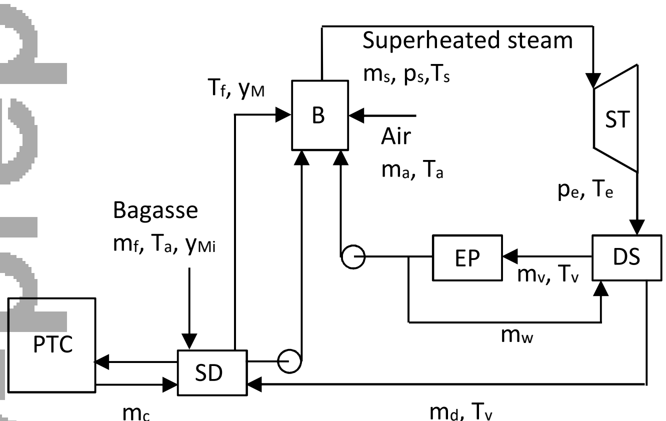

Fig 1 Cogeneration system integrated with parabolic trough collector and steam dryer

3. MODELS OF SYSTEM COMPONENTS

3.1 Boiler

Boilers used in sugar factories are industrial boilers. The recent model of industrial boiler presented by Chantasiriwan [5] is used for simulation in this paper.

3.2 Steam turbine

A common type of steam turbine found in many sugar factories in Thailand is back-pressure turbine. The power output (P) of steam turbine can be determined if turbine efficiency (η_t) is known. It is expressed as

$$P = m_s \eta_t \left(h_s - h_{es}\right) \quad (1)$$

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

3.3 Desuperheater

Evaporation process requires saturated steam. However, the temperature of exhaust 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 exhaust steam is mixed with saturated liquid water. The mass flow rate of saturated liquid water (m_w) is determined from mass and energy balances of desuperheater:

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

where h_e, h_v, and h_l are enthalpies of exhaust steam, saturated steam, and saturated liquid 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

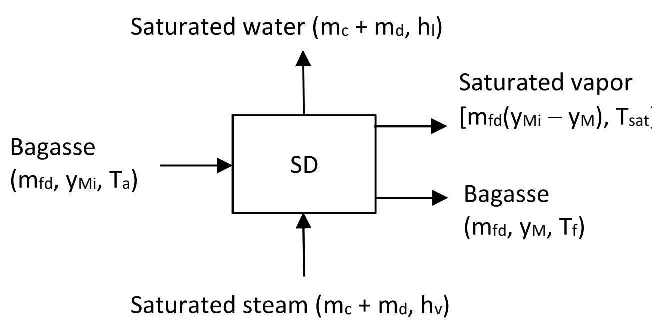

Fig 2 Steam dryer model

The model of steam dryer is shown in Fig. 2. Saturated steam from desuperheater and parabolic trough collector is used to remove some of bagasse moisture. 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 y_{Md}, which is 0.1. 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.

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

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

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

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

3.6 Parabolic trough collector

Parabolic trough collector consists of a parabolic reflector and a receiver located at the focus of the reflector. Sunlight incident on the reflector is concentrated on the receiver, which consists of two concentric tubes known as the absorber and the cover. The concentrated sunlight heats the fluid flowing inside the absorber. The vacuum between the absorber and the cover reduces heat loss from the absorber to the surroundings.

Working fluid may be synthetic oil that can reach a high temperature without boiling. The fluid exchanges heat with saturated liquid water in a heat exchanger to produce saturated steam. Alternatively, saturated steam may be generated directly in the parabolic trough collector without the need for an intermediate fluid. This configuration is known as the direct steam generation.

Ideally, the entire solar energy incident on the parabolic trough collector is focused onto the receiver. Therefore, the ideal amount of solar energy reaching the receiver is

$$Q_{ideal} = G_b A_{ap} \cos\theta \quad (8)$$

where G_b is the solar direct beam irradiation, A_{ap} is the aperture area of the receiver, and θ is the incident angle. It is assumed that sun tracking system is used to keep the incident angle at 0°. The actual solar energy reaching the receiver is less than the ideal amount because of losses. The optical efficiency, which accounts for all losses, is defined as

$$\eta_{opt} = \frac{Q_{actual}}{Q_{ideal}} \quad (9)$$

The actual solar energy reaching the receiver will heat the absorber, which will increase the enthalpy of the working fluid. Thermal losses occurring in the absorber are accounted for by the thermal efficiency, which is defined as

$$\eta_{th} = \frac{m_c \Delta h_{vl}}{Q_{actual}} \quad (10)$$

4. RESULTS AND DISCUSSION

According to Rein [6], the composition of dry fibrous material in bagasse is 45.92% carbon, 43.89% oxygen, 5.67% hydrogen, 0.31% nitrogen, 0.04% sulfur, 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, T_a = 30°C, and η_t = 0.85. Furthermore, it is assumed that the juice processing capacity of the evaporation process (m_v) is 40 ton/h. Other boiler parameters for this simulation are provided by Chantasiriwan [5]

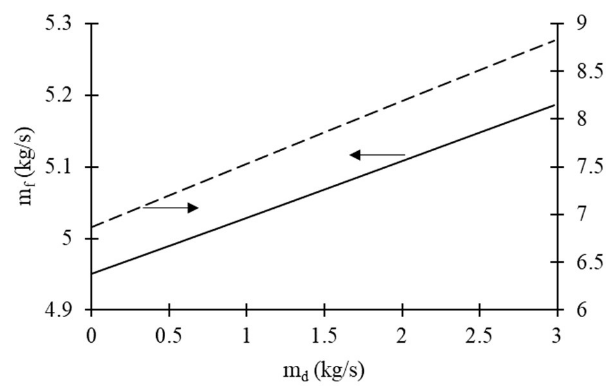

Fig 3 Variations of fuel flow rate (m_f) and power output of steam turbine (P) with mass flow rate of steam (m_d) in steam dryer in the cogeneration system that supplies saturated steam from desuperheater to steam dryer

Simulation results are first obtained for the cogeneration system in which steam dryer is supplied by saturated steam from only desuperheater (m_c = 0). Figure 3 shows that steam drying results in increasing mass flow rate of fuel (m_f) and increasing power output from steam turbine (P). Without steam drying (m_d = 0), m_f is 4.951 kg/s, and P is 6.870 MW. By supplying 1 kg/s of saturated steam to steam dryer (m_d = 1 kg/s), m_f is increased to 5.029 kg/s, and P is increased to 7.532 MW. Since the power-to-fuel ratio of the system without steam drying is 1.388 MJ/kg, whereas the power-to-fuel ratio of the system with steam drying is 1.498 MJ/kg, the system with steam drying is more energy efficient. It should be noted that the maximum steam flow rate in steam dryer is 2.98 kg/s because steam dryer is designed to reduce fuel moisture content to 10% on the dry basis (y_{Md} = 0.1).

Typically, the availability of bagasse in a sugar factory is limited. The use of saturated steam from only desuperheater for steam drying may, therefore, be infeasible if it requires more bagasse consumption. Parabolic trough collector may be used to supply additional saturated steam to steam dryer. It is found that the use of parabolic trough collector reduces bagasse consumption. System simulation indicates that, for a given value of m_d, there exists the corresponding mass flow rate of saturated steam from parabolic trough collector (m_c) that results in the value of 4.951 kg/s for the mass flow rate of bagasse. Figure 4 shows this variation of m_c with m_d.

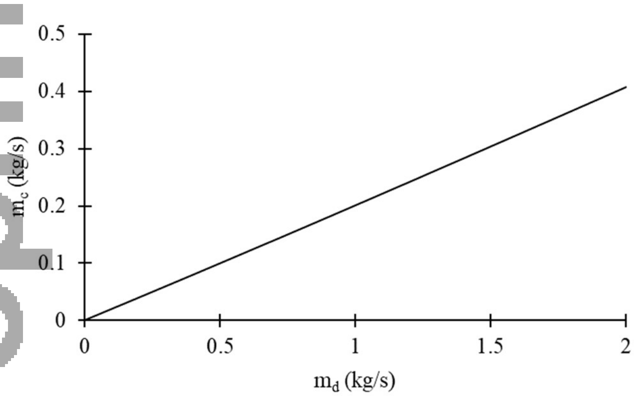

Fig 4 Variation of mass flow rate of steam from parabolic trough collector (m_c) with mass flow rate of steam from desuperheater (m_d) that results in the fuel consumption rate of 4.951 kg/s

In order to evaluate the economic feasibility of the integration of steam dryer and parabolic trough collector, let m_d be 1.0 kg/s. The value of m_c results in the fuel consumption rate (m_f) of 4.951 kg/s is 0.20 kg/s. Steam dryer reduces the wet-basis moisture content of bagasse from 52% to 42.8%. The rate of fuel moisture removal is 3549 kg/h. The cogeneration system integrated with both steam dryer and parabolic trough collector as shown in Fig. 1 will produce the power output of 7.54 MW. The parameters of parabolic trough collector are G_b = 632 W/m^2, η_{opt} = 0.75, and η_{th} = 0.7. The aperture area of the solar collector (A_{ap}) required to generate 0.20 kg/s of saturated steam is found to be 1326 m^2.

Assume that the unit cost of parabolic trough collector is 180 \$/m^2, and the unit cost of steam dryer is 100 \$/(kg/h). The total cost of installing them is \$594000. The cogeneration system integrated with steam dryer and parabolic trough collector yields 667 kW more power output than the cogeneration system without steam dryer and parabolic trough collector. Assume that all of the power output is converted to electricity. The operation period of parabolic trough collector is 8 hours per day, and the annual operation period of sugar factory is 5 months. Therefore, the gain in annual electrical energy generation is 800400 kW.h. If the electricity price is 0.10 \$/kW.h, the payback period for the investment in this system is about 7.5 years.

5. CONCLUSION

The integration of steam dryer and parabolic trough collector is proposed for cogeneration system of sugar industry. Steam dryer is used to reduce the moisture content of fuel for cogeneration system, which results in increasing system efficiency. Models of cogeneration system, steam dryer, and parabolic trough collector are used to demonstrate that this integration increases power output without changing fuel consumption rate. The simple payback period for the investment in this integration is found to be acceptable. Therefore, the integration of steam dryer and parabolic trough collector appears to be economically justified.

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