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Using Superheated Steam Dryer to Improve Cogeneration in Sugar Factory

Sarocha Charoenvai[1*] and Somchart Chantasiriwan[2]

[1] Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi,
Thanyaburi, Pathum Thani, 12110, Thailand
[2] Department of Mechanical Engineering, Faculty of Engineering, Thammasat University, Rangsit Campus,
Pathum Thani, 12121, Thailand
[*] Corresponding Author: sarochakuk@hotmail.com, +6689-117-0898

Abstract

The cogeneration system in sugar factories consists of four main components: the juice extraction unit, the evaporation unit, the steam generation unit, and the turbo-generation. The outputs of the juice extraction unit are sugar juice and bagasse. Juice is sent to the evaporation process. Bagasse is used as the fuel in the steam generation process. High-pressure steam can be used to produce power in back-pressure turbine. Steam from the turbine is superheated, and must be desuperheated to produce saturated steam. This study investigates the improvement of the cogeneration process by replacing desuperheater with superheated steam dryer. The results show that, under certain specified conditions, doing so increases the boiler efficiency by 6.71%, increases the power plant efficiency by 3.46% and reduces bagasse use by 2.44%. Furthermore, it can recover water that would be lost in flue gases. However, it generates slightly less power.

Keywords: Cogeneration, Extraction-Condensing Turbine, Sugar Manufacturing, Bagasse drying, Energy System

1. Introduction

In last few decades the research involving renewable energy sources has been growing. The biomass energy is a major source of energy available in nature, and has been widely studied due to the fear of possible future oil shortages. The use of biomass can reach up to 18% of total primary energy worldwide by the year 2050, which is four times the current use. Alves et al. [1] reported that biomass residues have a large energy potential for power generation, and highlights the need for proper exploration of these resides. The main agricultural products produced in the world, which consequently generate large amounts of waste and sugarcane, corn, wheat, rice, cassava and soybeans.

Sugar cane is one of the major agricultural crops in Thailand. Thai sugar factories have contributed to making Thailand a leading exporter of sugar to the world market, producing annually about 9.5 Mt of sugar [2]. An important by-product of sugar manufacturing process is bagasse, which used to be regarded as a waste, but is now used as fuel in cogeneration systems of almost all Thai sugar factories.

From energy viewpoint, raw sugar manufacturing with cogeneration may be considered as consisting of four main processes: juice extraction, juice evaporation (which includes crystallization), steam generation, and turbogenerator [3]. Sugar cane stalks are extracted for sugar juice in the juice extraction process, of which by-product is bagasse. Water is evaporated from sugar juice in the evaporation process to produce raw sugar. High-pressure steam required for this process is produced by the steam generation process, which uses bagasse from the evaporation process as input. The steam generation process is usually designed to generate steam that has a much higher pressure than the steam required by the juice evaporation process. Therefore, the steam output from this process is sent to the turbogenerator so that useful power is extracted in the steam expansion process. Steam leaving the turbogenerator is superheated. It is mixed with water in desuperheater before the resulting saturated steam is sent to the juice extraction process.

In order to increase juice extraction, water is added to the juice extraction process, which results in bagasse with high water content [3]. Combustion of moist bagasse is not efficient not only because a substantial amount of thermal energy is needed to evaporate water from bagasse, but also the amount of excess air required for complete combustion increases with bagasse moisture, leading to higher dry flue gas loss and low boiler efficiency. It has been shown that bagasse drying leads to higher boiler efficiency, and can save a considerable amount of fuel [4-6]. Flue gases exhausted from the steam generation process may be used to dry bagasse. However, practical problems have so far limited its use. One serious problem is a possibility of the combustion of dry bagasse in the flue gas dryer [7].

Superheated steam dryer is another type of dryer that may be used to dry bagasse effectively [8, 9]. An obvious advantage of superheated steam dryer compared with flue gas dryer is the minimal risk of bagasse combustion in the dryer. Furthermore, flue gas temperature may not be high enough to be used in flue gas dryer, or flue gas may be more efficiently used as the heating medium for other heat exchangers in the steam generation unit. Superheated steam available for drying bagasse may be exhausted from a back-pressure turbine. Since the evaporation process requires saturated steam, the temperature of the exhausted superheated steam may be reduced in the dryer, producing both bagasse with less moisture content and saturated steam required for the evaporation process. This paper presents a study of the improvement of a cogeneration system in sugar factories by replacing desuperheater with superheated steam dryer.

2. Basic Cogeneration System

Figure 1 shows the schematic of the basic cogeneration system in a hypothetical sugar factory. Bagasse from the juice extraction system enters the boiler (B) along with ambient air. The dry-basis moisture of the bagasse is x_m. Thermal energy released from the combustion leads the production of high-pressure steam and high-temperature flue gases. The superheated steam leaving the boiler is at the design pressure p_s and the design temperature T_s. The flue gases are assumed to be maintained at a fixed temperature T_g by installation of the right amount of heat transfer surfaces in the boiler. The type of turbine installed in this system is assumed to be the back-pressure turbine. The pressure at the exhaust of the turbine is p_e, which is the same steam pressure required by the evaporation process (EP). Exhaust steam is superheated. Its temperature depends on the isentropic efficiency of the turbine, which is assumed to be known. The required steam for EP is, however, saturated. Therefore, an appropriate amount (m_w) of cool water at a known temperature (T_w) must be mixed with superheated steam in the desuperheater (DS). Saturated steam will condense in EP, and becomes saturated water at the exit of EP. Some of the water is sent to the cooling process (CP) using cooling tower to reduce its temperature to T_w so that it will be ready for use in DS. The remaining water is used as feed water for the boiler.

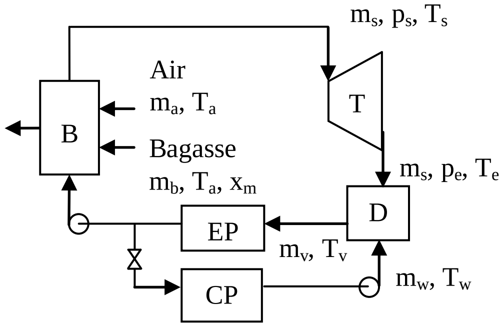

Fig. 1 Basic cogeneration system

Assume that the composition of dry bagasse is known, and the ash content in dry bagasse is negligible, the higher heating value (HHV) can be deter-mined from Dulong's formula [10].

$$HHV = x_C HHV_C + \left(x_H - \frac{x_O}{8} \right) HHV_H + x_S HHV_S \qquad (1)$$

where x_C, x_H, x_O, and x_S are mass fraction of C, H, O, and S, respectively, in dry bagasse. Higher heating values of C, H, and S are, respectively, HHV_C = 3.396 × 10^4 kJ/kg, HHV_H = 1.41890 × 10^5 kJ.kg, and HHV_S = 9.42 × 10^3 kJ.kg. In order to determine the lower heating value of bagasse, the amount of water resulting from the combustion of 1 kg of dry bagasse must be known. Since the complete combustion of 1 kg of dry bagasse produces $9x_H$ kg of water, the lower heating value of dry bagasse is

$$LHV = HHV - 9 x_H h_{fg} \qquad (2)$$

where h_{fg} is the latent heat of evaporation of water at the standard state (2.44 × 10^3 kJ/kg).

It is assumed that combustion of bagasse is complete. The amount of excess air required for the complete combustion of bagasse is assumed to be 35% (ϕ = 0.35). Therefore, the mass flow rate of air (m_a) can be computed as follows.

$$m_a = (1+\phi) AFR m_b \qquad (3)$$

where AFR is the stoichiometric air-fuel ratio.

$$AFR = 11.44 x_C + 34.32 x_H + 4.29 (x_S - x_O) \qquad (4)$$

Some of the heat released by combustion of bagasse is lost through radiation and convection between the boiler shell and the ambient air. If the fraction of heat losses is ε, the net heat input to the steam generation unit is

$$Q_{in} = (1-\varepsilon) m_b LHV \qquad (5)$$

It is assumed that the heat loss of 1.5% of the total heat released accounts for all heat losses.

Energy balance of the boiler requires that heat input is used to (1) increase the temperature of the moisture in bagasse to the saturation temperature, evaporate the water, and increase the temperature of the resulting vapor to T_g, (2) increase the temperature of flue gases to T_g, and (3) evaporate feed water, and increase its temperature to T_s. Therefore, the energy balance becomes

$$\begin{aligned} & m_b \{ (1-\varepsilon) LHV + \lfloor c_{pb} + (1+\phi) AFR c_{pa} \rfloor (T_a - T_r) - \\ & [1 + (1+\phi) AFR] c_{pg} (T_g - T_r) - x_m \lfloor c_{pw} (T_r - T_a) + h_{fg} \\ & c_{pv} (T_g - T_r)] \} = m_s (h_s - c_{pw} T_v) \qquad (6) \end{aligned}$$

where T_r is the reference temperature (25°C). The specific heat capacities of dry bagasse (c_{pb}), water (c_{pw}) and steam (c_{pv}) are, respectively, 0.46 kJ/kg.K, 4.18 kJ/kg.K and 1.80 kJ/kg.K. Since the combustion of bagasse is complete, the flue gases consist of CO_2, H_2O, O_2, N_2, and SO_2. The average heat capacities (c_{pg} and c_{pa}) are determined by taking into account the variation of the heat capacity of each gas with temperature according to Verbanck [11].

Mass and energy balances of DS are

$$m_v = m_s + m_w \tag{7}$$

$$m_v h_v = m_s h_e + m_w c_{pw} T_w \tag{8}$$

where h_v is the enthalpy of the saturated steam at the exit of the desuperheater, and h_e is the enthalpy of the superheated steam at the exhaust of the turbine. If the isentropic efficiency (η_t) is known, h_e is determined as follows.

$$h_e = h_s - \eta_t \left(h_s - h_{es}\right) \tag{9}$$

where h_{es} is the enthalpy of the exhaust steam having pressure p_e and the same entropy as the inlet steam. Equations (7) and (8) can be solved for ms in terms of m_v.

$$m_s = \left(\frac{h_v - c_{pw} T_w}{h_e - c_{pw} T_w}\right) m_v \tag{10}$$

After m_s has been determined, the mass flow rate of bagasse required for the system (m_b) can be found from Eq. (6). In addition, the power output of the turbine can also be found from

$$P = m_s \left(h_s - h_e\right) \tag{11}$$

3. System with Superheated Steam Dryer

Figure 2 shows the schematic of the modification of the basic cogeneration system, in which desuperheater is replaced with superheated steam dryer (SSD). In this system, bagasse is passed through SSD before entering the boiler. SSD uses exhaust steam from the turbine to remove some moisture from bagasse so that its dry-basis moisture decreases from x_m to x_{md}. Steam leaving SSD is saturated. Bagasse leaving SSD is at the steam saturation temperature, and has less moisture. It is assumed that the mass flow rates of steam required by EP in both systems are the same. As a result, the mass flow rate of steam in the modified system (m_{sd}) is different from that of the basic system (m_s). Due to pressure loss in SSD, steam must be exhausted at a higher pressure (p_{ed}) from the turbine. It is assumed that $p_{ed} = 1.1p_e$ to account for the pressure loss of 10% in SSD. It should be noted that, as a result of pressure change, the exhaust steam temperature is also changed from T_e in the basic cogeneration system to T_{ed} in the system with superheated steam dryer.

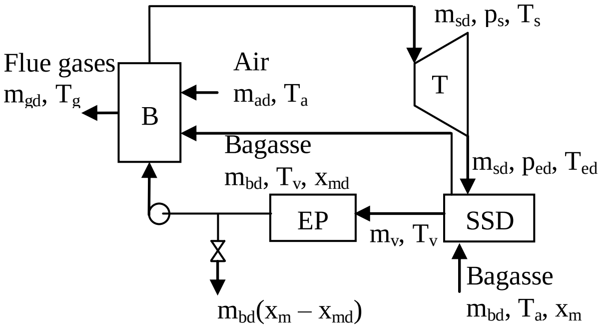

Fig. 2 Cogeneration system with superheated steam dryer

Mass and energy balances of SSD are

$$m_v = m_{sd} + m_{bd}\left(x_m - x_{md}\right) \tag{12}$$

$$m_{bd} c_{pb}\left(T_v - T_a\right) + x_m m_{bd} c_{pw}\left(T_v - T_a\right) + m_{bd}\left(x_m - x_{md}\right) h_{vl} = m_{sd} c_{pv}\left(T_{ed} - T_v\right) \tag{13}$$

where h_{vl} is the latent heat of evaporation of water at p_e. There are 3 unknowns in Eqs. (12) and (13), which are m_{bd}, m_{sd}, and x_{md}. Therefore, an additional equation for the determination of the three unknowns is required. It comes from energy balance of the boiler.

$$m_{bd}\left\{(1-\varepsilon)LHV + c_{pb}\left(T_v - T_r\right) + (1+\phi)AFRc_{pa}\left(T_a - T_r\right) - x_{md}\left[c_{pw}\left(T_r - T_v\right) + h_{fg} + c_{pv}\left(T_g - T_r\right)\right] - \left[1 + (1+\phi)AFR\right]c_{pg}\left(T_g - T_r\right)\right\} = m_{sd}\left(h_s - c_{pw} T_v\right) \tag{14}$$

After m_{sd} has been found, the power output of the turbine in this system is determined from

$$P_d = m_{sd}\left(h_s - h_{ed}\right) \tag{15}$$

4. Results and Discussion

According to Rein [7], the typical composition of dry ash-free bagasse is 47.89% C, 45.81% O, 5.92% H, 0.33% N, and 0.05% S. In order to carry out simulation, certain parameters of the systems must be provided. The values of these parameters are x_m = 1.0, p_s = 2 MPa, p_e = 200 kPa, T_s = 500°C, T_g = 150°C, T_w = 40°C, T_a = 30°C, m_v = 10 kg/s, and η_t = 0.9.

Simulation results are used to compare two important performance parameters of the basic system and the system with superheated steam dryer. Power plant efficiency and boiler efficiency are defined as

$$\eta_p = \frac{P}{m_b LHV} \tag{16}$$

$$\eta_b = \frac{m_s\left(h_s - c_{pw} T_v\right)}{m_b LHV} \tag{17}$$

for the basic system, and

$$\eta_{pd} = \frac{P_d}{m_{bd} LHV} \tag{18}$$

$$\eta_{bd} = \frac{m_{sd}\left(h_s - c_{pw} T_v\right)}{m_{bd} LHV} \tag{19}$$

for the system with superheated steam dryer. Additional parameters that are compared are the rates of bagasse use (m_b, m_{bd}) and the generated powers (P, P_d). Furthermore, it can be seen from Fig. 2 that the system with superheated steam dryer yields water recovery. The water is lost in the flue gases exhausted to the atmosphere in the basic system.

Table shows that system with superheated dryer has 6.71% larger boiler efficiency, 3.46% larger power plant efficiency, uses 2.44% less bagasse, but produces slightly less power. Furthermore, it can recover water that would lost in the basic system. The reduced power generation is the consequence of pressure loss in SSD. Decreasing this pressure loss will result in more power generation, which may exceed that of the basic system. By contrast, increasing pressure loss in SSD will result in lower power production. If power generation of the system with superheated steam dryer is not significantly less than that of the basic system, it is clearly advantageous to replace desuperheater with superheated steam dryer in the cogeneration system. However, a decision to replace desuperheater with superheated steam dryer will require more careful assessment if the pressure loss in SSD is large. In this case, it must be decided whether the reduced power generation is sufficiently compensated by the reduced bagasse use and the water recovery.

Table 1 Comparison between the basis system and the system with superheated steam dryer

Parameter	Basic system	System with SSD
Boiler eff. (%)	73.93	78.89
Power plant eff. (%)	14.18	14.67
Rate of bagasse use (kg/s)	2.46	2.40
Power (MW)	5.28	5.27
Water recovery (kg/s)	-	0.348

5. Conclusion

Models are developed to simulate performances of two cogeneration systems in the sugar industry. In the first system, cooling water is mixed with superheated steam exhausted from back-pressure turbine in desuperheater to produce saturated steam required for the sugar juice evaporation process. In the second system, the required saturated steam is produced by using superheated steam dryer with superheated steam and wet bagasse as inputs. A by-product of the second system is the recovery of water that would be lost with flue gases. With certain specified parameters and under the condition that the amount of saturated steam supplied to the evaporation process is fixed, the second system results in larger boiler and power plant efficiencies, less bagasse use, but slightly less power generation.

6. References

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