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Improving Cogeneration in Sugar Factories by Superheated Steam Drying of Bagasse

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Abstract

The typical cogeneration system in sugar factories uses moist bagasse as the fuel for the boiler, which generates high-pressure steam required by the back-pressure turbine to produce power output. Exhaust steam from back-pressure turbine is used for heating duty in the evaporation unit. Because the steam is superheated, it must be mixed with cooling water to produce saturated steam. Combustion of moist bagasse in the typical system is inefficient because substantial thermal energy is required to evaporate moisture in bagasse. In this paper, an investigation is made into the improvement of the typical system by using superheated steam dryer, in which superheated steam from the turbine exhaust is in direct contact with moist bagasse. It is found that the improved system reduces bagasse consumption and increase power plant efficiency. Furthermore, the improved system recovers water that would be lost with flue gases in the typical system.

Keyword: Cogeneration, Sugar manufacturing, Bagasse drying, Energy system, Modeling

INTRODUCTION

Power generation from biomass has increased its share of total power generation in many countries. Although prices of fossil fuels have dropped substantially in recent years, benefits of biomass power generation such as carbon neutrality and energy security have prevented governments of many countries from abandoning the policy of increasing dependence on power production from biomass. Among various types of biomass conducive to power generation, sugar cane is arguably the most important due the large number of cane sugar factories around the world. Most factories use bagasse, a by-product of the raw sugar manufacturing process, as the dominant fuel in generating steam that is required for the process. Almost all of these factories have discovered that, with the improvement of the process efficiency, there is surplus bagasse, and the most energy-efficient way is to couple the sugar factory with a thermal power plant because the surplus bagasse that can be used to generate exportable electrical power.

Cogeneration in sugar factory consists of four main processes: juice extraction, juice evaporation (which includes crystallization), steam generation, and turbo-generator [1]. Sugar juice is extracted from sugar cane stalks in the juice extraction process, of which by-product is bagasse. This process requires water addition to increase juice extraction, which results in diluted sugar juice and bagasse with high moisture content. The steam generation process uses bagasse from the juice extraction process as the fuel. It consists of a boiler that can generate high-pressure steam, which may be sent to the turbo-generator to produce useful power. Low-pressure steam required for the juice evaporation process is exhausted from back-pressure steam turbine. The evaporation process produces raw sugar by evaporating all water content from diluted sugar juice. It requires low-pressure saturated steam. Since the exhausted steam produced by the steam generation process is superheated, it must be mixed with the right amount of cooling water in a desuperheater before the resulting saturated steam is sent to the evaporation process.

Moist bagasse leaving the juice extraction process is normally delivered to the boiler in the steam generation process without being dried. Although the boiler is designed for operating with high-moisture bagasse, its efficiency is low because a substantial amount of thermal energy released from combustion is needed to evaporate water from bagasse, and the amount of excess air required for complete combustion increases with bagasse moisture content, leading to higher dry flue gases loss. It has been recognized that flue gases exhausted from the steam generation process may be used to dry bagasse, which results in an increase in boiler efficiency [2-5]. 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 [6]. Furthermore, flue gas dryer requires the temperature of hot gases in the range of 218°C – 330°C [4]. However, most steam generation units in sugar factories are equipped with economizers and air heaters to recovery energy from hot flue gases before exhausting them to the atmosphere, resulting in the final flue gas temperature of less than 200°C, which may not be high enough to be used in the flue gas dryer.

Another source of thermal energy available for bagasse drying is superheated steam. Advantages of superheated steam compared with flue gas drying include energy saving, reduced emission, low risk of combustion, and reduced drying time [7]. For cogeneration system in sugar factories, an additional advantage is that superheated steam is readily available in sugar factories at the exhaust of back-pressure turbine. This advantage is absent from other systems that require a heat source to generate superheated steam for drying materials such as pine chips [8], sawdust [9], corn grain [10], empty fruit bunch [11], and beet pulp [12].

The capability of superheated steam dryer for bagasse was previously demonstrated by Jensen [13] and Morgenroth and Batstone [14]. Although superheated steam available for drying bagasse is exhausted from back-pressure turbine, the standard practice in a typical sugar factory does not make use of its availability. Instead the superheated steam is mixed with cooling water in a desuperheater to produce saturated steam required for the evaporation process. An obvious improvement over this practice is to use superheated steam to remove moisture from bagasse. This paper presents the construction of the mathematical models of the typical cogeneration system without superheated steam dryer and the improved cogeneration system with superheated steam dryer. Both models are then compared to demonstrate the advantages of the improved cogeneration system.

TYPICAL COGENERATION SYSTEM

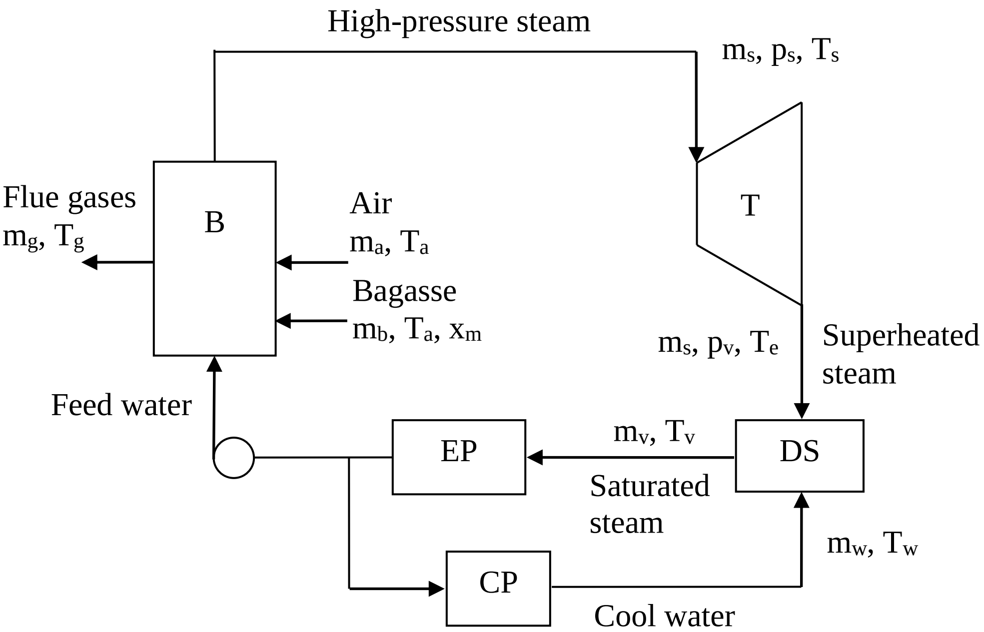

Figure 1. Typical cogeneration system

Figure 1 shows the schematic of the typical cogeneration system in a sugar factory. Bagasse from the juice extraction system enters the boiler (B). The dry-basis moisture content of bagasse is x_m. Thermal energy released from the combustion of bagasse and ambient air results in the production of high-pressure steam and high-temperature flue gases. The superheated steam leaving the boiler is at pressure p_s and temperature T_s. Due to the installation of economizer and air heater in the boiler, the temperature of flue gases will drop to a low value at the exit from the boiler. It is assumed that this temperature (T_g) is known. The type of turbine installed in this system is the back-pressure turbine. The pressure at the exhaust of the turbine is p_v, which is steam pressure required by the evaporation process (EP). Exhaust steam is superheated. Its temperature (T_e), which is larger than the saturation temperature (T_v), depends on the pressure and temperature (p_s and T_s) of steam entering the turbine, and the isentropic efficiency (η_t) of the turbine. For instance, if p_s = 4200 kPa, T_s = 440°C, and η_t = 0.7, the steam temperature at the exit of the turbine (T_e) 184.8°C, and the magnitude of superheat ($T_e - T_v$) is 64.6°C. 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 either cooling pond or 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.

Assume that the composition of dry bagasse is known, the higher heating value (HHV), expressed in dry basis, can be determined the formula proposed by Qian et al. [15].

$$\text{HHV} = 873.52\left(\frac{1}{3}x_C + x_H + \frac{1}{8}x_S\right) \tag{1}$$

where x_C, x_H, and x_S are mass fractions of C, H, and S, respectively, in dry bagasse. In order to determine the lower heating value of dry 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

$$\mathrm{LHV} = \mathrm{HHV} - 9x_H\Delta h_r \tag{2}$$

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

It is assumed that the product from combustion of bagasse does not consist of CO. The amount of excess air required for the combustion of bagasse depends on bagasse moisture content. According to Rein [6], dry bagasse requires 17% of excess air ($\phi = 0.17$), and the excess air requirement of moist bagasse is given by

$$\phi = 47.57y_m^3 + 58.00y_m^2 + 23.99y_m - 3.18 \tag{3}$$

where y_m is the wet-basis moisture content of bagasse; $y_m = x_m/(1 + x_m)$. Equation (3) is to be used for $0.4 \le y_m \le 0.6$. Once the excess air is known, the mass flow rate of air (m_a) can be computed as follows.

$$m_a = (1+\phi)\mathrm{AFR}m_b \tag{4}$$

where AFR is the stoichiometric air-fuel ratio.

$$\mathrm{AFR} = 11.44x_C + 34.32x_H + 4.29(x_S - x_O) \tag{5}$$

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

$$Q_{in} = (1-\varepsilon)m_b\mathrm{LHV} \tag{6}$$

where m_b is the mass flow rate of dry bagasse. The heat loss parameter ε accounts for two sources of heat losses ($\varepsilon = \varepsilon_r + \varepsilon_c$). It is assumed that the heat loss from radiation and convection between the boiler shell and the ambient air is 1.5% of the total heat released by combustion ($\varepsilon_r = 0.015$). In addition, there is unburned carbon that is a result of the difficulty of burning all moist bagasse completely. It has been found that the amount of unburned carbon depends on bagasse moisture content. According to Rein [6], $\varepsilon_c = 0.010$ for dry bagasse, and

$$\varepsilon_c = 3.953y_m^3 + 5.000y_m^2 + 2.154y_m - 0.298 \tag{7}$$

for $0.4 \le y_m \le 0.6$.

Energy balance of the boiler requires that heat input is used to (1) evaporate feed water, and increase its temperature to T_s, (2) increase the temperature of flue gases to T_g, (3) increase the temperature of the vapor resulting from the evaporation of bagasse moisture to T_g, and (4) increase the temperature of inert ash to T_g. Therefore, the energy balance equation can be expressed as

$$\begin{aligned} &m_b\{(1-\varepsilon)\mathrm{LHV} + [(1-x_A)c_{pb} + (1+\phi)\mathrm{AFR}c_{pa}](T_a - T_r) - [1+(1+\phi)\mathrm{AFR} - x_A]c_{pg}(T_g - T_r) - \\ &x_m[c_{pw}(T_r - T_a) + c_{pv}(T_g - T_r)] - x_A c_{pash}(T_g - T_a)\} = m_s(h_s - c_{pw}T_v) \end{aligned} \tag{8}$$

where x_A is the mass fraction of ash in dry bagasse, T_a is the ambient temperature, and T_r is the reference temperature (25°C). The specific heat capacities of dry bagasse (c_{pb}), water (c_{pw}), steam (c_{pv}), and ash (c_{pash}) are, respectively, 0.46, 4.18, 2.20, and 1.00 kJ/kg.K. 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 [16].

Mass and energy balances of DS are

$$m_v = m_s + m_w \tag{9}$$

$$m_v h_v = m_s h_e + m_w c_{pw} T_w \tag{10}$$

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 of turbine (η_t) is known, h_e is determined as follows.

$$h_e = h_s - \eta_t(h_s - h_{es}) \tag{11}$$

where h_{es} is the enthalpy of the exhaust steam having pressure p_v and the same entropy as the inlet steam. Equations (9) and (10) can be solved for m_s in terms of m_v.

$$m_s = \left(\frac{h_v - c_{pw}T_w}{h_e - c_{pw}T_w}\right)m_v \tag{12}$$

With m_s determined, the mass flow rate of dry bagasse required for the system (m_b) can be found from Eq. (8). In addition, the power output of the turbine and the power plant efficiency can be found. The power output is

$$P = \eta_m m_s(h_s - h_e) \tag{13}$$

where η_m is mechanical efficiency, which is assumed to be 0.95. The power plant efficiency is defined as the power output divided by the heating value of dry bagasse consumed by the boiler.

$$\eta = \frac{P}{m_b.\mathrm{LHV}} \tag{14}$$

IMPROVED COGENERATION SYSTEM

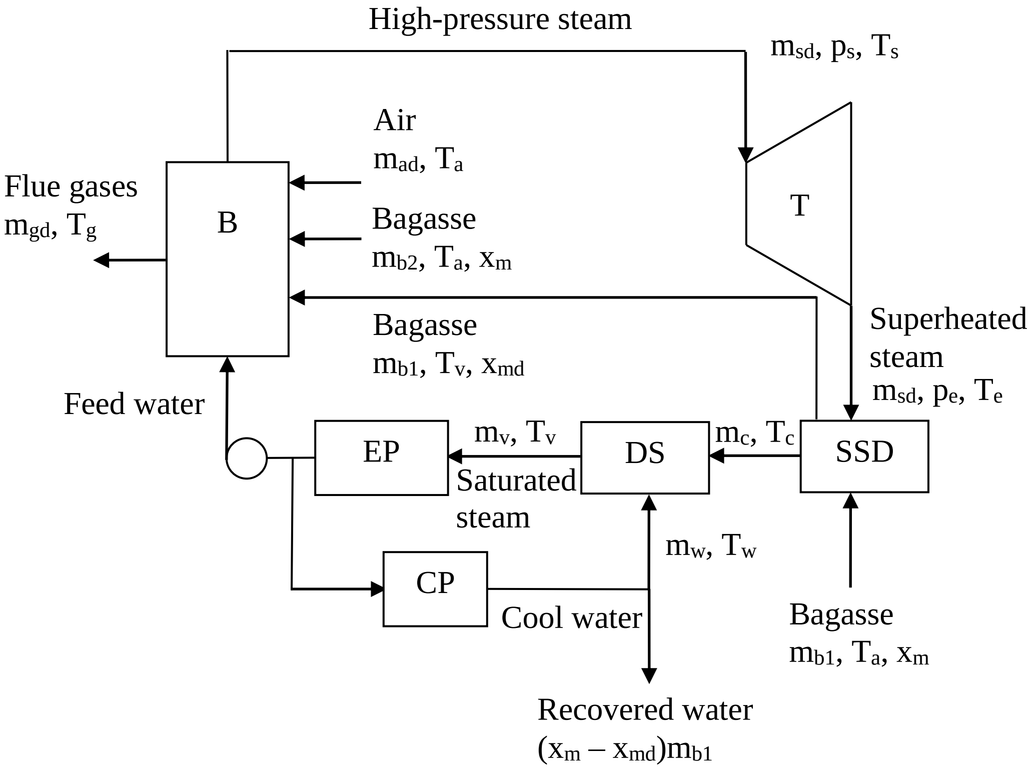

Figure 2. Improved cogeneration system

Figure 2 shows the schematic of the improved cogeneration system, in which superheated steam dryer (SSD) is added between T and DS. In this system, the total amount of bagasse is divided into two parts. Moist bagasse in the first part is passed through SSD. Mixing between bagasse and superheated steam causes some of the moisture in bagasse to evaporate, and the dry-basis moisture content to reduce from x_m to x_{md} before entering the boiler. The second part is moist bagasse at the ambient temperature. SSD uses superheated steam from the turbine exhaust to remove some moisture from bagasse. The pressure p_e of the exhaust steam is larger than the pressure p_v in EP to allow for pressure loss in SSD. Due to the finite size of SSD, steam leaving SSD is still slightly superheated ($T_c > T_v$). Therefore, it must be mixed with cooling water from CP to produce saturated steam required by EP. It is assumed that the mass flow rate of steam required by EP in this system is the same as in the typical system. Saturated steam will condense in EP, and becomes saturated water at the exit of EP. Some of the water is sent to the boiler, and the remaining water is sent to CP. It should be noted that not all of water sent to CP is used as cooling water for DS.

The mass flow rate of recovered water is

$$m_{rw} = (x_m - x_{md})m_{b1} \tag{15}$$

Mass and energy balances of SSD are

$$m_c = m_{sd} + m_{b1}(x_m - x_{md}) \tag{16}$$

$$(1-x_A)m_{b1}c_{pb}(T_v - T_a) + x_{md}m_{b1}c_{pw}(T_v - T_a) + x_A m_{b1}c_{pash}(T_v - T_a) +$$
$$m_{b1}(x_m - x_{md})\left[c_{pw}(T_v - T_a) + \Delta h_v + c_{pv}(T_e - T_v)\right] = m_{sd}c_{pv}(T_e - T_c) \tag{17}$$

where Δh_v is the latent heat of water evaporation at T_v. The energy balance of the boiler is

$$m_{b1}\left\{(1-\varepsilon_1)\mathrm{LHV} + (1-x_A)c_{pb}(T_v - T_r) + (1+\phi_1)\mathrm{AFR}c_{pa}(T_a - T_r)\right\} +$$
$$m_{b2}\left\{(1-\varepsilon_2)\mathrm{LHV} + (1-x_A)c_{pb}(T_a - T_r) + (1+\phi_2)\mathrm{AFR}c_{pa}(T_a - T_r)\right\} = m_{sd}\left(h_s - c_{pw}T_v\right)$$

$$+m_{b1}\left[1+\left(1+\phi_1\right)\mathrm{AFR}-x_A\right]c_{pg}\left(T_g-T_r\right)+m_{b2}\left[1+\left(1+\phi_2\right)\mathrm{AFR}-x_A\right]c_{pg}\left(T_g-T_r\right)$$

$$+x_{md}m_{b1}\left[c_{pw}\left(T_r-T_v\right)+c_{pv}\left(T_g-T_r\right)\right]+x_m m_{b2}\left[c_{pw}\left(T_r-T_a\right)+c_{pv}\left(T_g-T_r\right)\right]$$

$$+x_A m_{b1}c_{pash}\left(T_g-T_v\right)+x_A m_{b2}c_{pash}\left(T_g-T_a\right) \tag{18}$$

Once m_{sd} is found, the power output of the turbine and the power plant efficiency are determined from

$$P_d=\eta_m m_{sd}\left(h_s-h_e\right) \tag{19}$$

$$\eta_d=\frac{P_d}{\left(m_{b1}+m_{b2}\right).\mathrm{LHV}} \tag{20}$$

RESULTS AND DISCUSSION

According to Rein [6], the typical composition of dry bagasse is 45.92% C, 43.89% O, 5.67% H, 0.31% N, 0.04% S, and 4.17% A. In order to carry out simulation, certain parameters of the systems must be provided. The values of these parameters are p_s = 4200 kPa, T_s = 440°C, p_v = 200 kPa, T_w = 40°C, T_a = 30°C, T_g = 150°C, m_v = 50 kg/s, η_t = 0.7, and x_{md} = 0.1.

An important parameter in both the typical and improved systems is bagasse moisture content. It increases with the amount water added to the juice extraction process [1]. The optimum amount of water addition can be determined, and it results in the wet-basis moisture content of about 50%. Moist bagasse is normally stored before being fed as a fuel to the boiler. Since many sugar factories keep bagasse on an open ground, the moisture content of bagasse may decrease due to drying in the sun or increase due to exposure to rain. Therefore, it is assumed that the wet-basis moisture content (y_m) varies from 0.4 to 0.6.

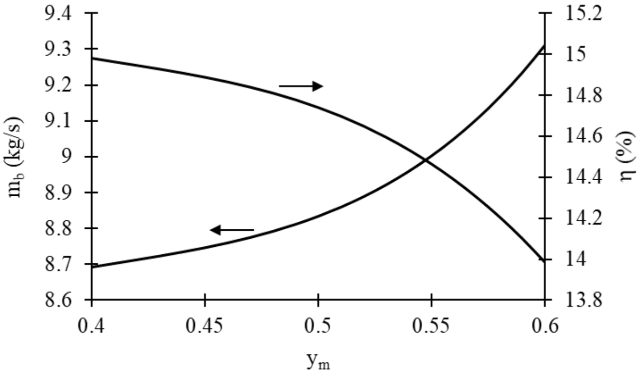

Figure 3. Effects of bagasse moisture content (y_m) on the rate of dry bagasse consumption (m_b) and the power plant efficiency (η) in the typical cogeneration system.

Figure 3 shows the effects of bagasse moisture content on the mass flow rate of dry bagasse consumed by the boiler and the power plant efficiency in the typical cogeneration system. In order to supply the fixed amount of saturated steam required by the evaporation system (which is 50 kg/s), the system requires more dry bagasse as bagasse moisture content increases. Increasing bagasse moisture content also leads to lower plant efficiency as more thermal energy is used to evaporate bagasse moisture, and less thermal energy is available for conversion to turbine power output. Under the assumed conditions, the typical system generates the same power output of 2.224×10^4 kW regardless of bagasse moisture content. The reason for this is that the decreasing plant efficiency is compensated by the increasing rate of dry bagasse consumption.

Three important performance parameters are compared between the typical system and the improved system. They are the percentage decrease in the rate of dry bagasse consumption (Δ_b), the percentage decrease in the power output (Δ_P), and the percentage increase in the power plant efficiency (Δ_η). They are defined as

$$\Delta_b=100\left(1-\frac{m_{b1}+m_{b2}}{m_b}\right) \tag{21}$$

$$\Delta_P=100\left(1-\frac{P_d}{P}\right) \tag{22}$$

$$\Delta_\eta=100\left(\frac{\eta_d}{\eta}-1\right) \tag{23}$$

All parameters are affected by not only bagasse moisture content but also two parameters related to the design of superheated steam dryer. The first parameter is the pressure-loss parameter, defined as

$$k=\frac{p_e}{p_v} \tag{24}$$

Because of pressure loss in SSD, k is larger 1. The second parameter is the degree of superheat in the steam leaving SSD, defined as

$$s=T_c-T_v \tag{25}$$

Due to the finite size of SSD, s is larger than zero. In this study, k and s are assumed to be 1.05 and 5°C, respectively.

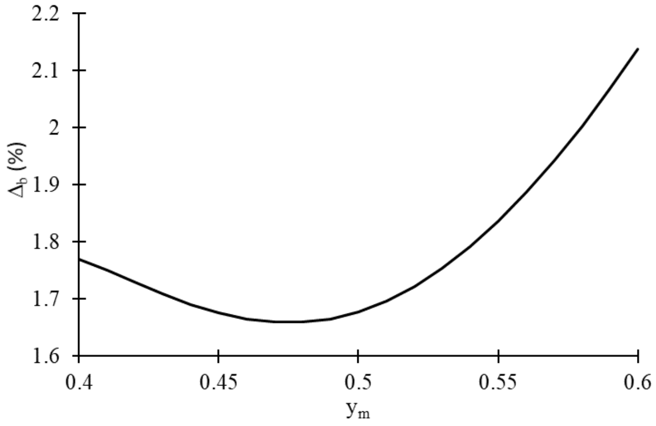

Figure 4. Variation of the percentage decrease in the rate of dry bagasse consumption (Δ_b) with bagasse moisture content (y_m).

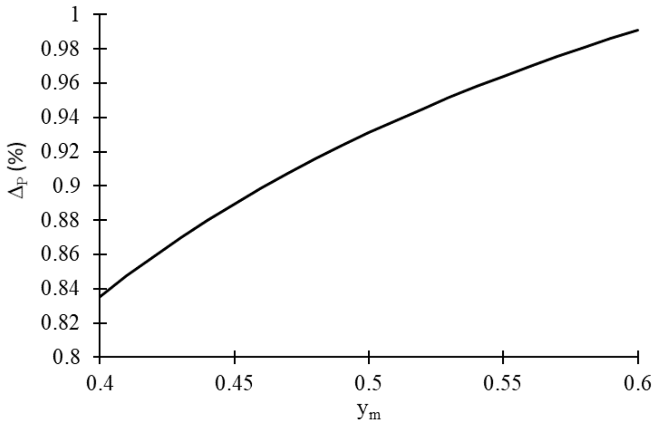

Figure 5. Variation of the percentage decrease in the power output (Δ_P) with bagasse moisture content (y_m).

Figure 4 shows that the percentage reduction of dry bagasse consumption increases with bagasse moisture content. The reason for this is that superheated steam drying results in bagasse with less moisture content, which leads to higher boiler efficiency. Figure 5 shows that the power output of the improved system is lower than that of the typical system. The reason for this is that the less exhaust steam is required by the improved system than the typical system because moisture removed from bagasse in SSD is converted to process steam supplied to EP. The power output of the improved system decreases with increasing bagasse moisture content. Figure 6 shows that the power plant efficiency of the improved system is larger than that of the typical system. The reason for this is that the decrease in dry bagasse consumed by the improved system is relatively larger than the decrease in power output. The performance of the improved system can also be measured in terms of the flow rate of recovered water. The variation of the water recovery flow rate with bagasse moisture content is plotted in Fig. 7. It can be seen that more water is recovered as bagasse moisture content increases.

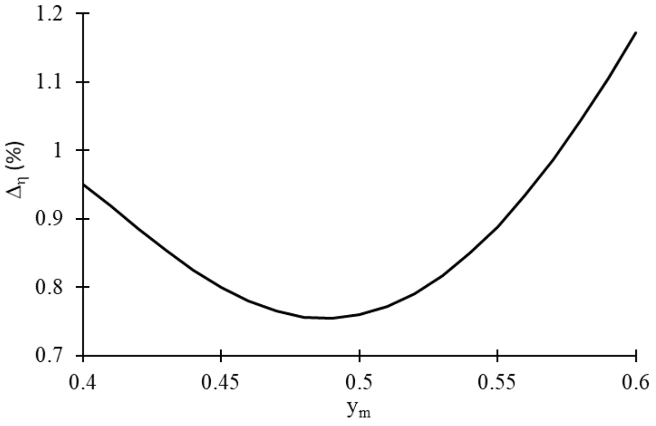

Figure 6. Variation of the percentage increase in the power plant efficiency (Δ_η) with bagasse moisture content (y_m).

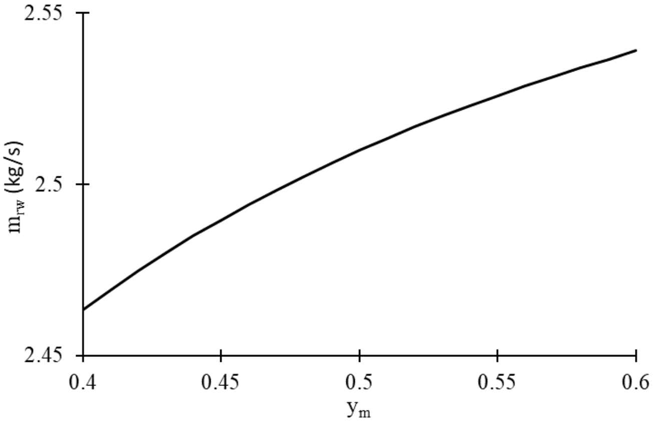

Figure 7. Variation of the flow rate of recovered water (m_{rw}) with bagasse moisture content (y_m).

Although simulation results show advantages of the improved system, it should be noted that these advantages come with investment cost and technical risks. The addition of the desuperheater and associated instruments may represent a significant fraction of the total investment cost of the cogeneration system. Operation and maintenance costs of the desuperheater must also be given serious consideration. Technical risks of the improved system result from the possibilities of contamination of feed water from bagasse particles and sugar juice. These risks may be reduced by the installation of additional equipment that separates contaminants from feed water before it is fed to the boiler. It is interesting to note that, according to BS 2486: 1997, the limit to the concentration of dissolved solids in feed water for a boiler operating at a pressure of 4200 kPa is 2000 ppm. Therefore, the investment cost of such equipment may not be unaffordable.

CONCLUSION

Models of two cogeneration systems are developed to compare their performances. The first system is the typical system found in sugar factories; it uses desuperheater to mix cooling water with superheated steam exhausted from back-pressure turbine to supply saturated steam to the sugar juice evaporation process. The second system uses superheated steam dryer to remove moisture from bagasse before feeding it to the boiler and to reduce the superheated steam before sending it to the desuperheater. The mass flow rate of dry bagasse consumption and the power plant efficiency are compared between the improved and the typical systems. Simulation results show that, under the condition that both systems require the same amount of saturated steam, the dry bagasse consumption of the improved system is less than that of the typical system, and the power plant efficiency of the improved system is larger than that of the typical system. In addition, the improved system recovers water that would be lost with flue gases in the typical system.

List of Symbols and Abbreviations

AFR	stoichiometric air-fuel ratio
c_p	specific heat capacity, kJ/kg.°C
HHV	higher heating value, kW/kg
h	enthalpy, kJ/kg
Δh	latent heat of water evaporation, kJ/kg
k	pressure-loss parameter
LHV	lower heating value, kW/kg
m	mass flow rate, kg/s
P	power output, kW
p	pressure, kPa
Q	heat transfer rate, kW
s	degree of superheat, °C
T	temperature, °C
x	mass fraction
x_m	dry-basis moisture content
y_m	wet-basis moisture content

Greek Symbols

Δ	percentage decrease or increase of performance parameter, %
ϕ	excess air ratio
η	efficiency

Subscripts

a	ambient
b	dry bagasse
d	dryer
e	turbine exhaust
g	flue gas
r	reference
rw	recovered water
s	steam
t	turbine
v	evaporation system

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