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Improving Cogeneration of Sugar Factory by Replacing Desuperheater with Superheated Steam Dryer

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Abstract: From energy viewpoint, the cogeneration system in sugar factories consists of four main processes: juice extraction, evaporation, steam generation, and turbo-generator. The juice extraction process converts sugar cane into extracted juice and bagasse. The juice is evaporated in the evaporation process, and bagasse is sent to the steam generation process. Combustion between bagasse and air in the steam generation unit produces high-pressure steam, which is used to drive the turbo-genenerator. Steam exhausted from the turbo-genenerator is superheated, and must be desuperheated before being used to evaporate sugar juice in the evaporation process. The standard practice is to mix the superheated steam with cooling water in the desuperheater to produce saturated steam. In this paper, an investigation is made into the improvement of the cogeneration process by replacing desuperheater with superheated steam dryer. It is found that the improvement leads to increased steam flow rate, but less bagasse flow rate, which results in higher boiler and power plant efficiencies.

Keywords: *Cogeneration, Sugar Manufacturing, Bagasse Drying, Energy System, Modeling*

Introduction:

Cogeneration is widely implemented in factories that manufacture raw sugar from sugar cane. 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. 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 much higher pressure that 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 then 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. 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. It has been recognized that flue gas exhausted from the steam generation process may be used to dry bagasse, which leads to an increase in the efficiency of the steam generation process [1 – 4]. 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 [5].

Superheated steam dryer is another type of dryer that may be used to dry bagasse effectively [6, 7].(Jensen, 2003; Morgenroth and Batstone, 2005). 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. Depending on the type of turbine installed in the cogeneration system, superheated steam available for drying bagasse may either be exhausted from a back-pressure turbine or extracted from a condensing-extraction turbine. Since the evaporation process requires saturated steam, the temperature of the exhausted or extracted superheated steam must be reduced. The standard practice is to effect this temperature decrease by using desuperheater, in which mixing between the superheated steam and cooling water occurs. In this paper, an investigation is made into how the performance of the cogeneration system is improved by replacing desuperheater with superheated steam dryer.

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 ps 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 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.

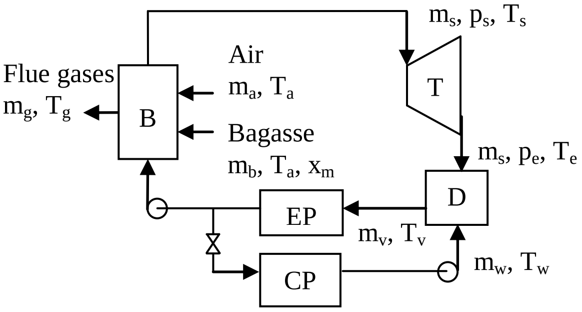

Figure 1: Basic cogeneration system

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 determined from Dulong's formula [8].

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

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

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

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.

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

where AFR is the stoichiometric air-fuel ratio.

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

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

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

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

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

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 inot account the variation of the heat capacity of each gas with temperature according to Verbanck [9].

Mass and energy balances of DS are

$$m_v = m_s + m_w \quad (7)$$

$$m_v h_v = m_s h_e + m_w c_{pw} T_w \quad (8)$$

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.

$$h_e = h_s - \eta_t (h_s - h_{es}) \quad (9)$$

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.

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

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

$$P = m_s (h_s - h_e) \quad (11)$$

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 xm to xmd. 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).

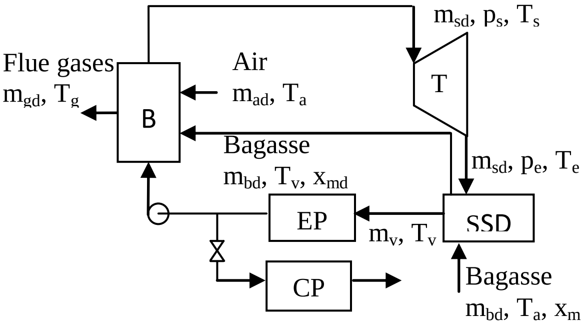

Figure 2: Cogeneration system with superheated steam dryer

Mass and energy balances of SSD are

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

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

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.

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

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

$$P_d = m_{sd}\left(h_s - h_e\right) \qquad (15)$$

Results and Discussion:

According to Rein [5], 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, $T_s = 500°C$, $T_w = 40°C$, $T_a = 30°C$, $m_v = 10$ kg/s, and $\eta_t = 0.9$. It should be noted that flue gas temperature (T_g) is considered to be a free parameter, of which variation affects performances of the systems.

Consider the base case, in which $T_g = 150°C$. Simulation for the basic system yields results shown in Table 1. Power plant efficiency (η_p) and boiler efficiency (η_b) are defined as

$$\eta_p = \frac{P}{m_b LHV} \qquad (16)$$

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

Simulation for the cogeneration system with superheated dryer yields results shown in Table 2. Power plant efficiency (η_{pd}) and boiler efficiency (η_{bd}) are defined as

$$\eta_{pd} = \frac{P_d}{m_{bd} LHV} \qquad (18)$$

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

It can be seen that the system with superheated dryer has a larger steam flow rate, and uses less bagasse, which results in higher power plant and boiler efficiencies.

Table 1: Simulation results in the base case for the basic system

Parameters	Values
m_s (kg/s)	9.374
m_b (kg/s)	2.463
m_w (kg/s)	0.626
P (kW)	5280
η_p (%)	14.18
η_b (%)	73.93

Table 2: Simulation results in the base case for the system with superheated steam dryer

Parameters	Values
m_{sd} (kg/s)	9.709
m_{bd} (kg/s)	2.402
x_{md}	0.879
P_d (kW)	5468
η_{pd} (%)	15.06
η_{bd} (%)	78.51

Flue gas temperature depends on surfaces of heat exchangers such as superheater, economizer, and air heater in the boiler. By installing more surfaces, T_g may be reduced. The reason for assuming a fixed value of T_g is that the boiler is designed to have suitable heat exchanger surfaces. Figure 3 shows variations of m_b, m_{bd}, m_s, and m_{sd} with T_g. It can be seen that all parameters increase with T_g. Correspondingly, η_b, η_{bd}, η_p, and η_{pd} decrease with increasing T_g.

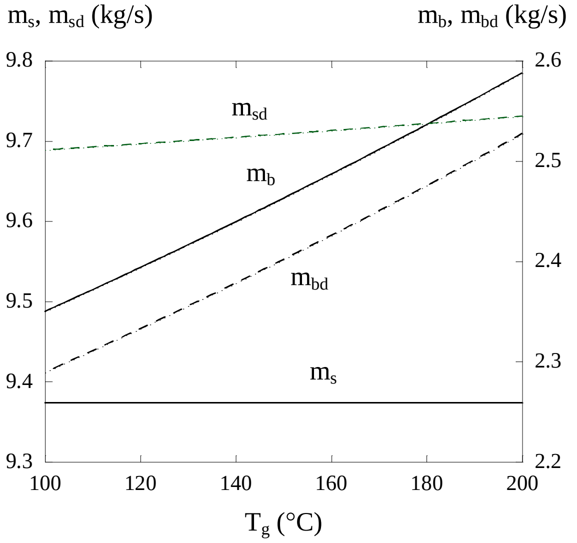

Figure 3: Effects of flue gas temperature on mass flow rates of bagasse and steam in the basic system and the system with superheated dryer

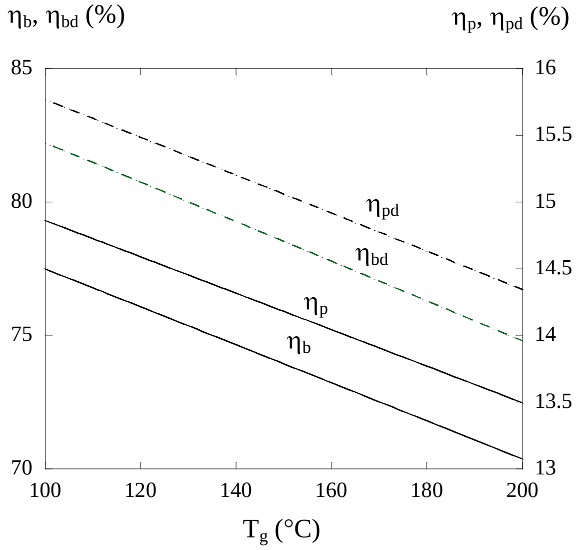

Figure 4: Effects of flue gas temperature on boiler and power plant efficiencies in the basic system and the system with superheated dryer

Conclusion:

In the cogeneration system of sugar factory, steam exhausted from back-pressure turbine must be de-superheated before being sent to the evaporation process, in which water is evaporated from sugar juice. Models are develop the simulate performances of two systems. In the first system, water is mixed with superheated steam in desuperheater. In the second system, superheated steam is used to dry bagasse in superheated steam drying. Under the condition that the amount of steam supplied to the evaporation process is fixed, the second system requires more steam flow rate, but less steam flow rate. Therefore, replacing desuperheater with super-heated steam dryer results in higher boiler and power plant efficiencies. Efficiencies decrease as flue gas temperature increases.

References:

[1] Maranhao, L. E. C. (1986) “Seven years' experience with bagasse dryers” Proceedings of the International Society of Sugar Cane Technologists, Vol. 3, pp. 44-61.

[2] Kinoshita, C. M. (1991) “Flue gas drying of bagasse” Applied Engineering in Agriculture, Vol. 7, pp. 729-734.

[3] Dixon, T. F., Joyce, K. N., and Treloar, R. (1998) “Increasing boiler capacity by dried bagasse firing” Proceedings of the Australian Society of Sugar Cane Technologists, Vol. 20, pp. 445-452.

[4] Gilberd, J., and Sheehan, M. (2013) “Modelling the effects of bagasse pre-drying in sugar mill boiler systems” Proceedings of the Australian Society of Sugar Cane Technologists, Vol. 35, pp. 337-343.

[5] Rein, P. (2007) *Cane Sugar Engineering*. Verlag, Berlin.

[6] Jensen, A. S. (2003) “Steam drying of beet pulp and bagasse” International Sugar Journal, Vol. 105, pp. 83-88.

[7] Morgenroth, B., and Batstone, D. (2005) “Development and prospects for drying bagasse by steam” International Sugar Journal, Vol. 107, pp. 410-415.

[8] Keating, E. L. (2007) *Applied Combustion*. CRC Press, Boca Raton.

[9] Verbanck, H. (1997) “Development of a mathematical model for watertube boiler heat transfer calculations” Proceedings of the South African Sugar Technologists' Association, Vol. 71, pp. 166-171.