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Comparison between Regenerative Feed Water Heating and Regenerative Fuel Drying in Biomass Power Plant

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Regeneration is a widely implemented method in a thermal power plant for increasing the power plant efficiency. In a typical regenerative method, extracted steam from a steam turbine is mixed with cooling water in an open feed water heater to increase feed water temperature before feed water is heated, and becomes superheated steam. An alternative method of regeneration is possible for a biomass power plant that consumes the fuel with high moisture content. In this method, extracted steam is used to decrease the fuel moisture content before the fuel is combusted. The main objective of this paper is to compare both methods of regeneration. The reference power plant consists of a biomass boiler, a steam turbine, a condenser, and an open feed water heater. The boiler consumes 5.2 kg/s of fuel with a moisture content of 52 %, and generates superheated steam with a pressure of 4.5 MPa. Steam is extracted from the steam turbine at a pressure of 1.2 MPa, and supplied to the open feed water heater. The condenser pressure is 10 kPa. Turbine isentropic efficiency is 85 %, and pump isentropic efficiency is 70 %. The power output of the reference power plant is 10.0 MW. Two methods of increasing the power output are compared. In the first method, another open feed water heater is added to the reference power plant. The pressure of extracted steam supplied to this open feed water heater is 0.2 MPa. In the second method, a steam dryer is added to the reference power plant. The pressure of extracted steam supplied to the steam dryer is also 0.2 MPa. Simulation results indicate the first method increases the power output up to 3 %, whereas the second method increases the power output up to 7 %.

1. Introduction

Feed water heating is a widely implemented method for increasing the efficiency of a thermal power plant. In this method, extracted steam from the steam turbine is used to increase feed water temperature before feed water enters the boiler. This method results in a higher power plant efficiency. Power plant efficiency increases with the number of feed water heaters (El-Wakil, 1984). However, there exists the optimum number of feed water heaters, which depends on the capacity of the power plant. A large thermal power plant may have as many as eight feed water heaters. By contrast, a small thermal power plant may have only one or two feed water heaters.

A thermal power plant powered by biomass fuel is known as a biomass power plant. Biomass fuels usually have high moisture contents. Combustion of moist fuel results in a low boiler efficiency because thermal energy from fuel combustion is required to evaporate fuel moisture, and water vapor has a higher specific heat capacity than dry flue gas. Fuel drying can increase the efficiency of a biomass boiler, which results in increasing power plant efficiency. An available source of thermal energy for fuel drying is extracted steam from a steam turbine. Two types of steam drying are possible. Direct steam drying requires direct contact between superheated steam and moist fuel. Sensible steam energy is transferred to moist fuel as superheated steam becomes saturated steam, which results in the reduction of fuel moisture content (Li et al., 2016). Indirect steam drying requires either superheated steam or saturated steam. No contact between steam and moist fuel occurs in this type of steam drying. Fuel moisture content is reduced due to heat transfer from condensing steam through metal walls to moist fuel. Indirect steam drying has several advantages compared with direct steam drying, such as higher energy efficiency, minimal cleaning of exhaust gas, smaller pressure drops, etc. (Devahastin and Majumdar, 2007). Several investigations of using indirect steam drying to increase energy efficiency have been carried out.

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The comparison between flue gas drying and steam drying in a biomass power plant that used pine chips as fuel was performed by Li et al. (2012). The integration of both air dryer and steam dryer in small power plants that used empty fruit bunches as fuel was found by Luk et al. (2013) to increase the overall energy efficiency of power generation. Gebreegziabher et al. (2014) demonstrated that further increase in the overall energy efficiency can be obtained by using low-pressure steam instead of medium-pressure steam for operating the steam dryer. Recently, Liu et al. (2017) performed thermodynamic and economic analyses of the integration of steam dryer in a biomass power plant, and found that the cost of steam dryer should be lower than an upper limit to justify its integration.

Both feed water heating and indirect steam drying require extracted steam as the heat source, and both methods result in increased power plant efficiency. Therefore, both methods may be considered as regeneration methods. However, regenerative feed water heating is much more in use than regenerative fuel drying. One reason for this is the lack of understanding of the advantages and disadvantages of regenerative fuel drying compared with regenerative feed water heating. The main objective of this paper is to compare both methods of regeneration. The reference power plant is assumed to be a biomass power plant with one open feed water heater. The efficiency of this power plant can be increased by adding either another open feed water heater or a steam dryer. It can be shown that, with the same power plant parameters, adding a steam dryer results in higher power output than adding another open feed water heater.

2. Reference biomass power plant

Due to its capability as a deaerator, open feed water heater is an essential component in a thermal power plant. Therefore, the biomass power plant with one open feed water heater shown in Figure 1 is considered as the reference power plant. Fuel combustion yields thermal energy that is used to generate superheated steam with the mass flow rate m_s, pressure p_s, and temperature T_s. Steam from the boiler (B) expands in the first steam turbine (ST1), and some power output is generated. Some steam is extracted from ST1 before the remaining steam expands in the second steam turbine (ST2), and additional power output is generated. The mass flow rate of extracted steam is ym_s. The mass flow rate of steam flowing in the condenser (C) is $(1 - y)m_s$. The outlet of C is assumed to be saturated liquid water, which is known as feed water. Feed water is pumped from C to the open feed water heater (FWH), in which extracted steam is mixed with feed water. Feed water at the outlet of FWH is sent to a pump before entering B.

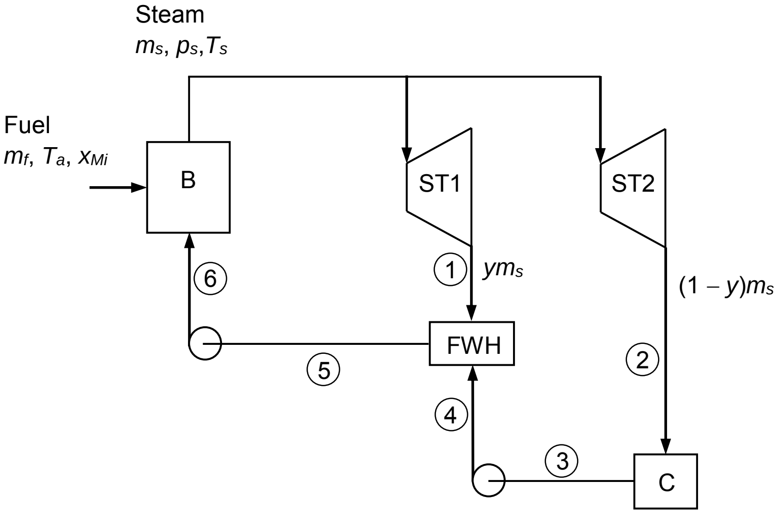

Figure 1: Reference biomass power plant.

The overall efficiency of a thermal power plant is defined as

$$\eta_o = \frac{P}{m_f HHV} \tag{1}$$

where m_f is fuel consumption rate, HHV is fuel higher heating value, and P is the net power output, which is the product of steam flow rate (m_s) and specific net work output (w_{net}). The overall power plant efficiency is the product of the boiler efficiency (η_b) and the thermal efficiency of Rankine cycle (η_{th}). These efficiencies are expressed as

$$\eta_b = \frac{m_s q_{in}}{m_f HHV} \tag{2}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} \tag{3}$$

where specific heat input (q_{in}) and net work output (w_{net}) are determined as follows.

$$q_{in} = h_s - h_6 \tag{4}$$

$$w_{net} = y(h_s - h_1) + (1-y)(h_s - h_2) - (1-y)(h_4 - h_3) - (h_6 - h_5) \tag{5}$$

Several previous investigations have assumed that boiler efficiency does not vary with inlet feed water temperature (T_6). This assumption is, however, incorrect. Li el al. (2018) showed that boiler efficiency decreased with increasing inlet feed water temperature. In order to avoid the shortcomings of previous investigations, the boiler model developed by Chantasiriwan (2019) will be used in this investigation.

3. Biomass power plant with two feed water heaters

The thermal efficiency of the reference biomass power plant is increased by adding a feed water heater. An illustration of biomass power plant with two feed water heaters is shown in Figure 2. The mass flow rate, pressure, and temperature of steam from boiler in this power plant are the same as those of the reference power plant. Furthermore, the condenser pressure is unchanged. There are three steam turbines (ST1, ST2, and ST3) and two feed water heaters (FWH1 and FWH2) in this power plant. FWH1 and FWH2 require extracted steam from ST1 and ST2 for feed water heating. The mass flow rates of extracted steam are ym_s and zm_s. The mass flow rate of steam expanding in ST3 and flowing to C is $(1 - y - z)m_s$. The outlet of C is again assumed to be saturated liquid water. Feed water is pumped from C to FWH2. Feed water at the outlet of FWH2 is pumped to FWH1. Feed water at the outlet of FWH1 is then sent to a pump before entering B.

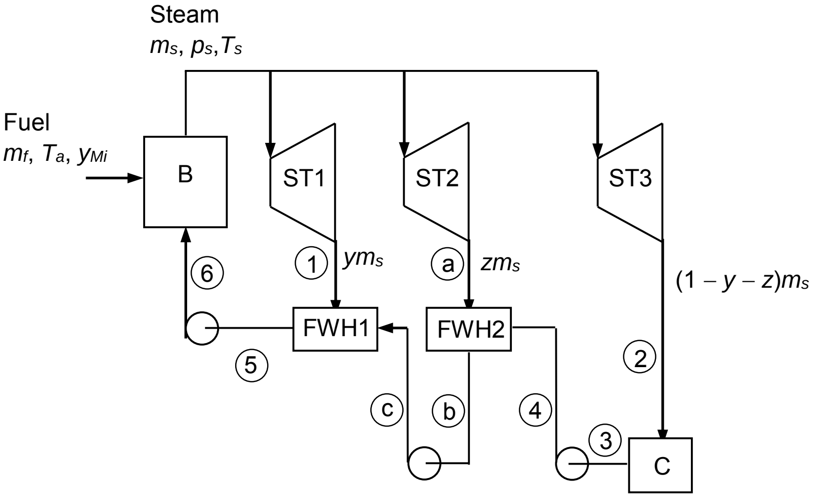

Figure 2: Biomass power plant with two feed water heaters.

The thermal efficiency of this power plant is determined from Eq(3). The expression of specific heat input (q_{in}) is the same as that of the reference biomass power plant [Eq(4)]. The expression of specific net work output (w_{net}) is different from that of the reference biomass power plant due to additional steam extraction;

$$w_{net} = y(h_s - h_1) + z(h_s - h_a) + (1-y-z)(h_s - h_2) - (1-y-z)(h_4 - h_3) - (1-y)(h_c - h_b) - (h_6 - h_5) \tag{6}$$

4. Biomass power plant with feed water heater and steam dryer

Extracted steam may be used to reduce the fuel moisture content instead of increasing the feed water temperature. For this purpose, a steam dryer is added to the reference biomass power plant. The result is a biomass power plant with an open feed water heater (FWH) and a steam dryer (SD) shown in Figure 3. FWH requires extracted steam from the first steam turbine (ST1), whereas SD requires extracted steam from the second steam turbine (ST2). The remaining steam is expanded in the third steam turbine (ST3), and sent to the condenser (C). Saturated liquid water at the outlet of C is pumped to FWH. Feed water at the outlet of FWH is pumped to B. Extracted steam from ST2 becomes saturated liquid water at the outlet of SD. Heat transfer from extracted steam to the fuel results in the decrease in fuel moisture content from x_{Mi} to x_M and the increase in fuel temperature from T_a to T_f. Model of steam dryer developed by Chantasiriwan (2021) is used in this investigation. Both x_M and T_f can be determined from given values of x_{Mi}, T_a, zm_s, and p_a using this model. Among these values, zm_s is the only variable. Increasing zm_s will result in decreasing fuel moisture content at the dryer outlet. It is assumed that the steam dryer is capable of reducing fuel moisture content to 30 %. Such a capacity of the steam dryer will place the upper limit on zm_s.

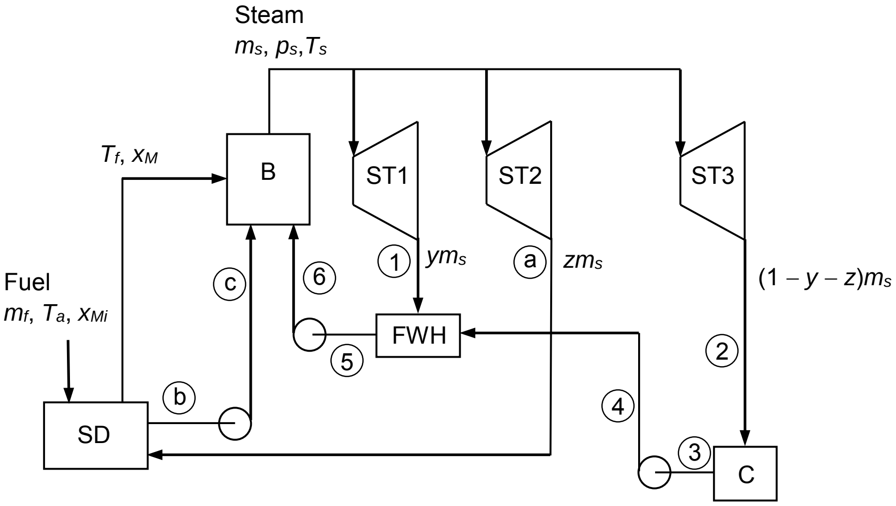

Figure 3: Biomass power plant with a feed water heater and a steam dryer.

The thermal efficiency of this power plant is determined from Eq(3). The expressions of specific heat input (q_{in}) and net work output (w_{net}) are as follows.

$$q_{in} = h_s - (1 - z)h_6 - zh_c \tag{7}$$

$$w_{net} = y(h_s - h_1) + z(h_s - h_a) + (1 - y - z)(h_s - h_2) - (1 - y - z)(h_4 - h_3) - z(h_c - h_b) - (1 - z)(h_6 - h_5) \tag{8}$$

5. Results and discussion

Parameters of the reference biomass power plant are p_s = 4.5 MPa, p_1 = 1.2 MPa, and p_2 = 10 kPa. According to the boiler model proposed by Chantasiriwan (2019), a boiler consists of a furnace and a set of heat exchangers (superheater, boiler bank, economizer, and air heater). The heat transfer areas of the superheater, the boiler bank, the economizer, and the air heater are, respectively, 290 m^2, 1,230 m^2, 1,270 m^2, and 1,420 m^2. The ambient air temperature is 30 °C. The biomass fuel has a higher heating value (*HHV*) of 8,796 kJ/kg. The wet-basis moisture content is 52 %. The fuel consumption rate is 5.2 kg/s. With these input parameters, the boiler model yields the values of 12.4 kg/s for the steam flow rate (m_s), 483 °C for the steam temperature (T_s), and 120°C for the exhaust flue gas temperature (T_{ge}), which is the temperature of flue gas at the boiler outlet. The power output increases with the extracted steam fraction (y). The upper limit of y that results in saturated liquid water at the outlet of FWH is 0.209. Assume that steam turbine and pump isentropic efficiencies are, respectively, 85 % and 70 %. The maximum power output is found to be 10 MW.

For the biomass power plant with two feed water heaters, p_a is 200 kPa. Results for this power plant are plotted in Figure 4. The extracted steam fraction of ST2 (z) is a variable in this plot. The extracted steam fraction of ST1

(y) is the maximum value that results in the output of FWH1 being saturated liquid water at pressure p_1. It can be seen that, with increasing z, the power output (P) increases, and y decreases. The maximum value of P is 10.3 MW. It occurs when z reaches the upper limit of 0.108. At this value, the output of FWH2 is saturated liquid water at pressure p_a.

For the biomass power plant with a feed water heater and a steam dryer, p_a is also 200 kPa. The increase in the extracted steam fraction of ST2 (z) in this power plant results in decreasing fuel moisture content at the boiler inlet, which leads to increasing boiler efficiency. Provided that the extracted steam fraction of ST1 (y) is the maximum value that results in the output of FWH1 being saturated liquid water at pressure p_1, the thermal efficiency of this power plant is quite insensitive to z. However, the power output of this power plant increases with z due to increasing boiler efficiency. Results for this power plant are plotted in Figure 5. It is found that y is nearly unchanged as z is varied. Therefore, the plot of y as a function of z is not shown. It can be seen from Figure 5 that, with increasing z, the power output (P) increases, and fuel moisture content at the dryer outlet (x_M) decreases. Comparing Figure 4 and Figure 5 reveals that, for the same value of z, the power output of the biomass power plant with a feed water heater and a steam dryer is larger than the power output of the biomass power plant with two feed water heaters. Furthermore, the upper limit of z of the biomass power plant with a feed water heater and a steam dryer, which is 0.148, is larger than that of the biomass power plant with two feed water heaters. The upper limit is reached when the fuel moisture content at the dryer outlet is 30 %. The maximum value of P is 10.7 MW.

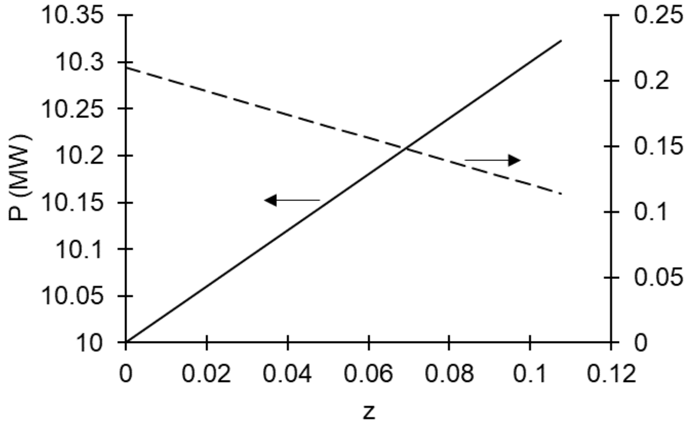

Figure 4: Effects of the extracted steam fraction from ST2 (z) on the power output (P) of the biomass power plant with two feed water heaters and the extracted steam fraction from ST1 (y) that results in saturated liquid water at the outlet of FWH1.

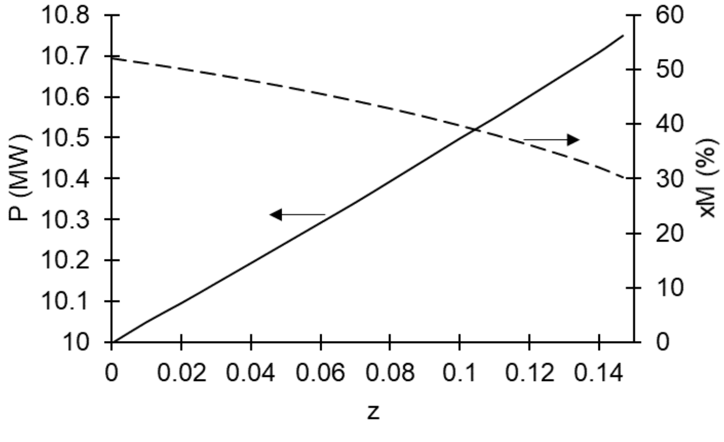

Figure 5: Effects of the extracted steam fraction from ST2 (z) on the power output (P) of the biomass power plant with a feed water heater and a steam dryer and the fuel moisture content at the dryer outlet (x_M).

Decreasing fuel moisture content results in decreasing exhaust flue gas temperature. The reason for this is that, with less fuel moisture content, the amount of water vapor in flue gas and the mass flow rate of flue gas decrease, which results in less heat content in flue gas. Normally, this temperature should be above the lower limit to avoid cold-end corrosion. It is assumed that the lower limit is 120 °C. In order to maintain exhaust flue gas temperature at this value, the air heater area must be reduced. For example, if z is 0.1, the fuel moisture content will be 39.7 %. If the air heater area is 1,420 m^2, the exhaust flue gas temperature will be 110.4 °C, and the power output will be 10.58 MW. In order to increase the exhaust flue gas temperature to 120 °C, the air heater area must be reduced to 1,060 m^2, which will also reduce the power output to 10.50 MW. Results shown in Figure 5 are obtained under the condition that the air heater area is reduced to the value that results in the exhaust flue gas temperature equal to 120 °C.

6. Conclusions

Regenerative feed water heating and regenerative fuel drying are compared in this paper. Both methods of regeneration require extracted steam from a steam turbine, and increase the overall power plant efficiency. Regenerative feed water heating requires the mixing of extracted steam and feed water in an open feed water heater in order to increase feed water temperature. Regenerative fuel drying uses heat transfer from condensation of extracted steam to reduce the fuel moisture content in an indirect steam dryer. Comparison is made under the conditions that Rankine cycle parameters and boiler parameters are the same. Results are obtained for a case study, in which the reference biomass power plant operates at the maximum and minimum pressures of 4.5 MPa and 10 kPa. The reference biomass power plant consists of an open feed water heater, which is supplied by extracted steam at a pressure of 1.2 MPa. The power output of the reference biomass power plant is 10 MW. By adding another open feed water heater to the reference biomass power plant, the power output may be increased to the maximum value of 10.3 MW if the pressure of extracted steam supplied to the feed water heater is 200 kPa. Adding a steam dryer, however, can increase the power output to the maximum value of 10.7 MW, i.e., regenerative fuel drying is more energy efficient than regenerative feed water heating for a biomass power plant that consumes a fuel having a high moisture content.

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