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Blowdown Heat Recovery Using Hybrid Fuel Drying System in Biomass Power Plant

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A hybrid fuel drying system is a system that uses both a steam dryer and a flue gas dryer for fuel drying. This system is particularly suitable for a biomass power plant because its fuel may have a high moisture content. The previously proposed hybrid drying system uses extracted steam to operate the steam dryer. Exhaust vapor from the steam dryer is used for the heating of combustion air in an air preheater. Flue gas dryer is installed at the outlet of boiler to reduce flue gas temperature to 120 °C. In this paper, it is proposed that steam requirement of steam dryer could be met by using flash steam from blowdown heat recovery system. A comparative analysis of two power plants is carried out in this paper. The reference power plant consumes 11.23 kg/s of biomass fuel having 50 % moisture content. The boiler of this power plant supplies 26.74 kg/s of steam at pressure 6.0 MPa and temperature 497.5 °C. The blowdown rate is 4 %, and there is no blowdown heat recovery. The net power output of the reference power plant is 25.0 MW. The modified power plant is integrated with the proposed heat recovery system. It consumes the same amount of fuel, and uses the same boiler. The blowdown heat recovery system supplies flash steam at pressure 250 kPa to steam dryer. The boiler supplies flue gas at temperature 143.7 °C to flue gas dryer. Both dryers are used to reduce fuel moisture content from 50 % to 47.4 %, and increase combustion air temperature from 25 °C to 37.2 °C. As a result of drier fuel and hotter air, the boiler generates 26.84 kg/s of steam at temperature 525.4 °C. The net power output of the modified power plant is 26.02 MW, which is 4.1 % higher than that of the reference power plant. Furthermore, it can be shown that the proposed system is economically attractive.

1. Introduction

A thermal power plant is a system that converts chemical energy to electrical energy. It consists of boiler, Rankine cycle, and generator. Boiler converts chemical energy to thermal energy. Rankine cycle converts thermal energy to mechanical energy. Generator converts mechanical energy to electrical energy. The overall efficiency of the power plant depends on boiler efficiency, thermal efficiency, and generator efficiency. Raising any of these efficiencies results in an increase in the overall power plant efficiency. Generator efficiency is quite high (around 98 %), and no further improvement is unlikely. Thermal efficiency depends on steam pressure, steam temperature, and condensing pressure. Various measures such as reheating and regeneration may be used to increase thermal efficiency subjected to thermodynamic, technical, and economic constraints. It is likely that these measures have already been implemented in a thermal power plant, and the practical upper limit of thermal efficiency of the power plant has already been reached. Unlike generator and thermal efficiencies, there seem to be existing opportunities to increase boiler efficiency.

A source of boiler losses is blowdown loss. Blowdown is the removal of water from steam drum to maintain the concentration of dissolved solids in steam drum at an acceptable level. Blowdown water has high pressure and temperature. Therefore, the discharge of blowdown water without heat recovery is responsible for energy inefficiency of the boiler system. The standard practice for recovering blowdown heat is using it to increase feed water temperature before feed water is fed to boiler. Two-stage blowdown heat recovery system was studied by Bahadori and Vuthaluru (2010). Mohammadi et al. (2015) showed that blowdown recovery could increase net generated power output, energy efficiency, and exergy efficiency. Several schemes of feed water heating using blowdown heat were analyzed by Chauhan and Khanam (2019). Other methods of blowdown heat

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recovery have also been proposed. Noroozian et al. (2017) presented a system that used Pelton turbines to generate power output from high-pressure blowdown water. Kocabas and Savas (2021) considered using flash steam unit combined with reverse osmosis system for blowdown heat recovery. Saedi et al. (2022) proposed using blowdown heat for radiant floor heating system in a greenhouse.

A study by Chantasiriwan (2021b) shows that using extracted steam for feed water heating is less energy efficient than fuel drying. Based on this study, an alternative method of blowdown heat recovery was proposed for biomass-fired power plant (Chantasiriwan, 2023b) and coal-fired power plant (Chantasiriwan, 2023c). The integration of steam dryer results in high exhaust flue gas temperature. Two methods of reducing flue gas temperature and increasing boiler efficiency are increasing heating surface areas of economizer and air heater and installing flue gas dryer (Chantasiriwan, 2021c). For power plants that use biomass fuels having high moisture contents, using both flue gas dryer and steam dryer to reduce fuel moisture contents seems to be an attractive option. Recently, it was demonstrated by Chantasiriwan (2023a) that hybrid drying system that uses both types of fuel dryer is technically and economically feasible.

In this paper, hybrid drying system is proposed as a viable method of blowdown heat recovery. The following sections described the reference biomass power plant and the proposed blowdown heat recovery system. Simulation results are then presented to showcase the advantages of this method of blowdown heat recovery.

2. Biomass power plant

Biomass power plant with one feed water heater is shown in Figure 1. Steam with mass flow rate m_s, pressure p_s, and temperature T_s is generated in boiler (B). The mass flow rate, temperature, and fuel moisture content of fuel consumed by boiler are m_f, T_a, and x_{Mi}. Steam is expanded in steam turbine (T) in two stages. The mass flow rate of extracted steam after the first stage is ym_s. The remaining steam is exhausted from steam turbine after the second stage. Exhaust steam condenses completely in condenser (C), resulting in saturated feed water. The pressure of feed water is increased before it is mixed with extracted steam from the first stage in feed water heater (FWH). The pressure of the resulting feed water is increased before feed water is sent boiler.

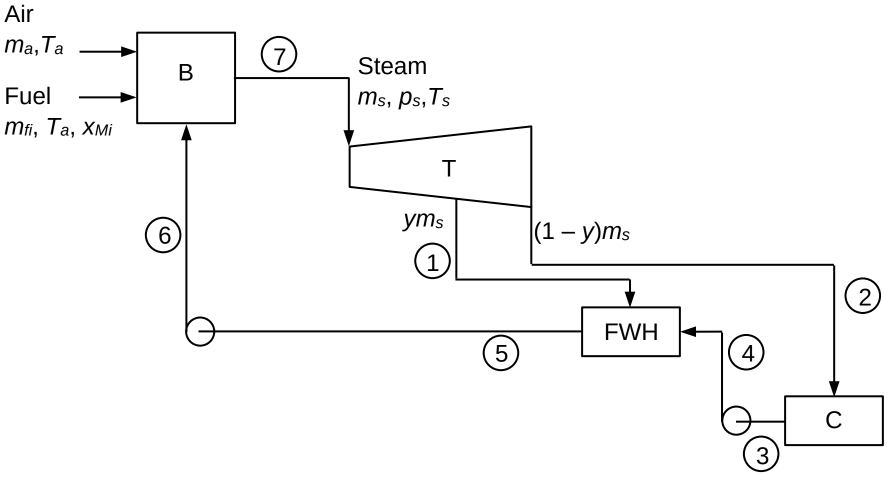

Figure 1: Reference biomass power plant.

The gross power output of the power plant is expressed as

$$P_{net} = ym_s(h_s - h_1) + (1-y)m_s(h_s - h_2) - (1-y)m_s w_{p1} - m_s w_{p2} \tag{1}$$

where h_s is determined from p_s and T_s, h_1 is determined from the isentropic efficiency (η_{t1}) during steam expansion from p_s to p_1, h_2 is determined from the isentropic efficiency (η_{t2}) during steam expansion from p_1 to p_2, w_{p1} and w_{p2} are determined from pressure drops across the two pumps and pump efficiency (η_p). The steam flow rate (m_s) and temperature (T_s) depend on boiler parameters (Chantasiriwan, 2021c), which are fuel flow rate, fuel composition, fuel temperature, air flow rate and temperature, and inlet feed water temperature. If boiler heating surface areas are specified, m_s and T_s can be determined.

The inlet feed water temperature (T_6) depends on h_5, which is determined from energy balance of FWH.

$$h_5 = yh_1 + (1-y)h_4 \tag{2}$$

The upper limit of y corresponds to state 5 being saturated liquid. It is assumed that y is less than the upper limit in order to reduce the risk of cavitation in the first pump. T_5 is assumed to equal the saturation temperature at p_1 minus 10 °C. This condition determines y as shown in Eq. (2).

The overall efficiency of the power plant is

$$\eta_o = \frac{P_{net}}{m_f HHV} \tag{3}$$

where HHV is fuel higher heating value, and P_{net} is the net power output, which is the product of gross power output and gross-to-net efficiency (η_{gn}). Thermal and boiler efficiency are expressed as

$$\eta_{th} = \frac{P_{gross}}{m_s(h_s - h_6)} \tag{4}$$

$$\eta_b = \frac{m_s(h_s - h_6)}{m_f HHV} \tag{5}$$

Thermal efficiency increases with steam temperature. Boiler efficiency increases as inlet air temperature is increased or fuel moisture content is decreased (El-Wakil, 1984). It will be shown in the following sections that the proposed blowdown heat recovery system is capable of increasing both efficiencies.

3. Blowdown heat recovery system

During steam generation in boiler, feed water is partially evaporated in evaporator. The resulting wet saturated steam is then separated into saturated water and dry saturated steam in steam drum. Saturated water is returned to evaporator. Dry saturated steam is heated in superheater. Due to impurities in feed water, and negligible amount of impurities in dry saturated steam, the rate of increase in concentration of impurities in drum water will be positive unless something is done to control it. A control method may be implemented by allowing a small quantity of water to leave steam drum. This method is known as blowdown. It should be noted that blowdown water must be replaced with make-up water of the same quantity to maintain an unchanging level of drum water.

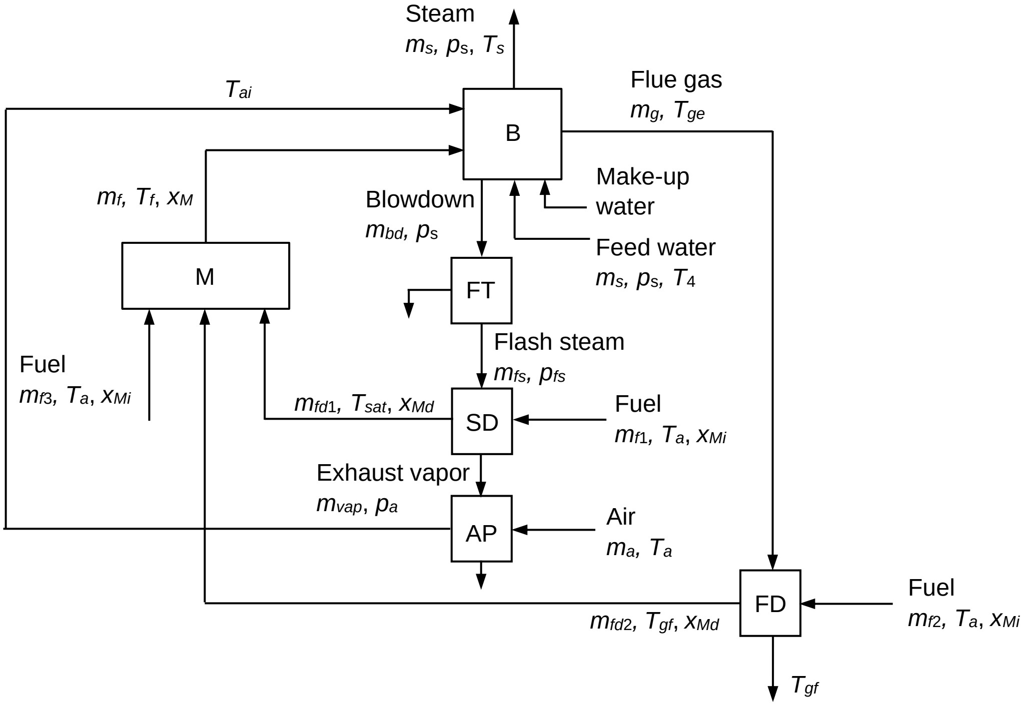

Figure 2: Proposed blowdown heat recovery system.

Without heat recovery, blowdown may result in a significant boiler heat loss. A blowdown heat recovery system is proposed in this paper, and is depicted in Figure 2. There are flash tank (FT), steam dryer (SD), air preheater (AP), and flue gas dryer (FD) in this system. Blowdown water is sent to flash tank. Its pressure is decreased from p_s to p_d, resulting in flash steam and saturated liquid water. Flash steam with mass flow rate m_{fs} is supplied to steam dryer. The first portion of fuel (with mass flow rate m_{f1}) is dried in steam dryer. The fuel moisture content is reduced from x_{Mi} to x_{Md}, the flow fuel flow rate is decreased to m_{fd1}, and the fuel temperature is increased to T_{sat} (100 °C). The moisture removed from fuel becomes exhaust vapor that leaves steam dryer at mass flow rate m_{vap}, which is the difference between m_{f1} and m_{fd1}. The exhaust vapor is the heat source for air preheater. Air temperature is increased in air preheater from T_a to T_{ai}, whereas exhaust vapor condenses completely. Heated combustion air is then sent to boiler (B). The second portion of fuel (with mass flow rate m_{f2}) is dried in flue gas dryer. The fuel moisture content is reduced from x_{Mi} to x_{Md}, the flow fuel flow rate is decreased to m_{fd2}, and the fuel temperature is increased to T_{gf}. Exhaust flue gas at temperature T_{ge} enters flue gas dryer, and leaves at temperature T_{gf}. The first and second portions of fuel are mixed with the third portion of fuel, which is undried, before the mixed fuel is fed to boiler. Since the total flue flow rate is specified as m_{fi}, the mass flow rate of the third portion is

$$m_{f3} = m_{fi} - m_{f1} - m_{f2} \tag{6}$$

After the three fuel portions are mixed, the mass flow rate, moisture content, and temperature are, respectively, m_f, x_M, and T_f. More detail of hybrid drying system is provided by Chantasiriwan (2123a).

Since there is less moisture in fuel and combustion air is hotter, the proposed blowdown heat recovery system enables the boiler to generate more steam at higher temperature. Therefore, the net power output of the power plant will increase as a result of higher thermal and boiler efficiencies.

Economic analysis of the proposed system can be carried out by computing the levelized cost of electricity (in \$/kW.h).

$$LCOE = \frac{C_{total}}{\Delta E_{el}} \tag{7}$$

where ΔE_{el} is the increase in generated electrical energy due to the integration of the blowdown heat recovery system, and C_{total} is the levelized total cost. If the both reference and modified power plants operate 8000 hours annually,

$$\Delta E_{el} = 8000 \Delta P_{net} \tag{8}$$

where ΔP_{net} is the difference between the net power output of the modified power plant and that of the reference power plant.

Capital costs of steam dryer and flue gas dryer are assumed to be proportional to moisture removal rates.

$$C_{sd} = 3600 c_{sd} \left(m_{f1} - m_{fd1} \right) \tag{9}$$

$$C_{fd} = 3600 c_{fd} \left(m_{f2} - m_{fd2} \right) \tag{10}$$

Capital cost of air preheater is assumed to be proportional to air preheater area.

$$C_{ap} = c_{ap} A_{ap} \tag{11}$$

Air preheater are is determined as follows.

$$A_{ap} = \frac{m_a c_{pa}}{U_{ap}} \ln \left(\frac{T_{sat,a} - T_a}{T_{sat,a} - T_{ai}} \right) \tag{12}$$

The overall heat transfer coefficient of the air preheater (U_{ap}) is 50 W/m^2.K. Assume that the capital recovery factor is 0.1, and operation and maintenance account for 15 % of the levelized capital cost. It should be noted that the cost of producing make-up water is assumed to be included in operation and maintenance cost. C_{total} is expressed as

$$C_{total} = 0.115 \left(C_{sd} + C_{fd} + C_{ap} \right) \tag{13}$$

The unit cost of a biomass dryer depends on the dryer type. It is assumed that steam dryer is rotary dryer, and flue gas dryer is flash dryer. According to Amos (1998), the ranges of unit costs were 300 - 796 \$/(kg/h) for rotary dryer and 550 – 1,600 \$/(kg/h) for flash dryer. Since the Chemical Engineering Plant Cost Index was 389.5 in 1998 and is 800.3 in 2024, these ranges are converted to 616 – 1,636 \$/(kg/h) for rotary dryer and 1130 – 3,287 \$/(kg/h) for flash dryer. The values of 1,126 \$/(kg/h) for c_{sd} and 2,209 \$/(kg/h) for c_{fd} are in the middle of these ranges, and are used in the calculation of C_{sd} and C_{fd} in Eqs. (9) and (10). The unit cost of air preheater can be estimated using a formula provided by Shamoushaki et al. (2021).

4. Results and discussion

Parameters of the reference biomass power plant are $p_s = 6.0$ MPa, $p_1 = 0.6$ MPa, and $p_2 = 9$ kPa. Biomass fuel consists of 51.5 % carbon, 41.6 % oxygen, 4.3 % hydrogen, 0.4 % nitrogen, 0.1 % sulfur, and 2.1 % ash on the dry basis. As-received fuel moisture content is 50 %. The ambient air temperature is 25 °C. The fuel consumption rate is 11.23 kg/s. The mass flow rate of combustion air is 40.78 kg/s. The inlet feed water temperature is 149.8 °C. The blowdown rate is 4 %. With these input parameters, a model of industrial boiler (Chantasiriwan, 2021c) yields the steam flow rate of 26.74 kg/s and the steam temperature of 497.5 °C. Isentropic efficiencies of steam turbine are 81.4 % and 82.5 % for η_{t1} and η_{t2}. Pump efficiency is 80 %. The net power output of the reference power plant is 25.00 MW. The gross-to-net efficiency is 97.5 %. The thermal and boiler efficiencies are 34.48 % and 70.59 %. The overall power plant efficiency of the reference power plant is 23.73 %.

The modified power plant is the reference biomass power plant integrated with the proposed blowdown heat recovery system. The flash tank decreases blowdown water pressure from 6 MPa to 250 kPa. Flash steam at pressure 250 kPa with mass flow rate 0.33 kg/s is generated as a result. The mass flow rate of flue gas is 51.34 kg/s. The temperature of flue gas at the boiler exit is 143.7 °C. It is decreased to 120 °C at the outlet of the flue gas dryer. The mass flow rates of fuel in the steam dryer and the flue gas dryer are 0.77 kg/s and 1.17 kg/s. Fuel moisture content is decreased from the initial value of 50 % to 30 % at the outlets of both dryers. The mass flow rate of undried fuel is 9.29 kg/s. The three fuel portions are mixed before the mixture is fed to the boiler. The mass flow rate, moisture content, and temperature of the mixed fuel are, respectively, 10.68 kg/s, 47.40 %, and 34.29 °C. The mass flow rate of exhaust vapor is 0.22 kg/s. It is used to increase combustion air temperature to 37.22 °C. With these input parameters, a model of industrial boiler (Chantasiriwan, 2021c) yields the steam flow rate of 26.84 kg/s and the steam temperature of 525.4 °C. The net power output of the modified power plant is 26.02 MW. The thermal and boiler efficiencies are 34.91 % and 72.54 %. The overall power plant efficiency is 24.69 %. Therefore, the integration of the blowdown heat recovery system increases the thermal, boiler, and overall efficiencies of the modified power plant.

The steam dryer removes 788 kg/h of moisture from the first fuel portion. The flue gas dryer removes 1208 kg/h of moisture from the second fuel portion. The heating surface area of the air preheater is 144 m^2. The levelized total cost is \$4.23 x 10^5. The increase in electrical energy due to the integration of the blowdown heat recovery system is 8.12 x 10^6 kW.h. Therefore, the levelized cost of electricity is 0.052 \$/kW.h. This number is lower than typical unit electricity prices (0.1 - 0.2 \$/kW.h). Therefore, the proposed system is economically attractive.

It is interesting to perform a sensitivity analysis with blowdown rate as the control parameter. Some results are shown in Figure 3. It can be seen that increasing blowdown rate from 4 % to 10 % results in 0.27 % increase in P_{net}. However, LCOE is also increased to 0.073 \$/kW.h. Therefore, the proposed system is economically less attractive as the blowdown rate is increased.

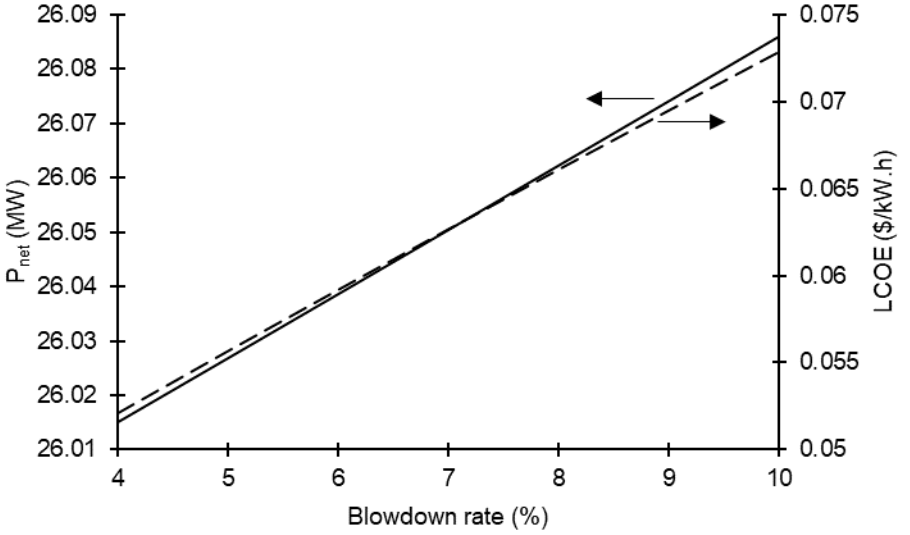

Figure 3: Variations of net power output of the modified power plant (P_{net}) and levelized cost of electricity (LCOE) with blowdown rate.

5. Conclusions

This paper presents a novel method of blowdown heat recovery. Hybrid drying system consisting of steam drying and flue gas drying is used in this method. The energy source of the steam dryer is flash steam that results from the pressure reduction of blowdown water in flash tank. The energy source of the flue gas dryer is high-temperature flue gas that leaves the boiler. Exhaust vapor that leaves the steam dryer is also used as the energy source for air preheater. The hybrid drying system reduces fuel moisture content and increases combustion air temperature, which enables the boiler to generate more steam at higher temperature. Simulation results show that the integration of the blowdown heat recovery system into the reference power plant that generates 25 MW of net power output is responsible for 4.1 % increase in the net power output. This method of heat recovery is economically feasible because the levelized cost of electricity is 0.052 \$/kW.h, which is lower than a typical monetary value of electricity. Additional simulation results show that more power output is generated as the blowdown rate is increased. However, this method is economically less attractive as the blowdown rate is increased. It should be noted that this conclusion is valid for a small biomass power plant that has a simple boiler-turbine circuit. Further study is needed to investigate the effects of the integration of the proposed blowdown heat recovery system into a power plant with a more advanced boiler-turbine circuit.

Nomenclature

A_{ap} – air preheater surface area, m^2
C_{ap} – air preheater cost, \$
C_{fd} – flue gas dryer cost, \$
C_{sd} – steam dryer cost, \$
h_s – steam enthalpy, kJ/kg
LCOE – levelized cost of electricity, \$/kW.h
m_a – air flow rate, kg/s
m_{f1} – fuel flow rate in steam dryer, kg/s
m_{f2} – fuel flow rate in flue gas dryer, kg/s
m_{fi} – fuel flow rate in boiler, kg/s
m_s – steam flow rate, kg/s
m_{vap} – exhaust vapor flow rate, kg/s
p_{fs} – flash steam pressure, kPa
P_{net} – net power output, MW
p_s – steam pressure, kPa
T_a – ambient air temperature, °C
T_{ai} – heated air temperature, °C
T_{ge} – flue gas temperature at boiler outlet, °C
T_{gf} – flue gas temperature at dryer outlet, °C
T_s – steam temperature, °C
T_{sat} – saturation temperature, °C
U_{ap} – overall heat transfer coefficient, $kW/m^2.°C$
x_{Md} – design fuel moisture content, %
x_{Mi} – initial fuel moisture content, %
y – extracted steam mass fraction, -
η_b – boiler efficiency, %
η_o – overall efficiency, %
η_{th} – thermal efficiency, %

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