Optimum Installation of Heat Recovery Devices in Biomass Boiler

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Abstract

Biomass boiler uses thermal energy from the combustion of biomass fuel and air to produce superheated steam from feed water. Biomass fuel usually has a high moisture content, which leads to low boiler efficiency. The boiler efficiency can be increased by using heat recovery devices to decrease the temperature of flue gas before it is exhausted from the boiler. Three heat recovery devices found in a typical installation of biomass boiler are economizer, air heater, and flue gas dryer. Economizer increases feed water temperature, air heater increases air temperature before combustion, and flue gas dryer decreases the moisture content of fuel. Limited available thermal energy of flue gas means that a decision must be made in selecting the sizes of these devices. The main objective of this paper is to use a biomass boiler model, in which the boiler consists of a furnace and a set of heat exchangers, to determine the optimum sizes of economizer, air heater, and flue gas dryer that minimize the total cost of installing them in biomass boiler system.

Keywords: Heat exchangers, Biomass drying, Energy system, Modelling

1. Introduction

Biomass fuels are usually characterized by high-moisture content. Combustion of a moist fuel in a biomass boiler results in low boiler efficiency because a large amount of thermal energy released from fuel combustion is required for the evaporation of moisture in the fuel. Drying of fuel requires an energy source. A high-temperature source like flue gas seems to be ideal for this purpose. Flue gas dryer is a heat recovery device that may be installed in a boiler to decrease flue gas temperature and increase boiler efficiency. Other heat recovery devices that are normally installed in a boiler are economizer and air heater. Thermal energy from flue gas increases feed water temperature in economizer and air temperature in air heater. All three heat recovery devices can effectively increase boiler efficiency. However, since all three devices require thermal energy from flue gas, there are limits to their sizes if they are installed together in a biomass boiler.

Studies of integrating flue gas dryer into biomass boiler system have been carried out by several investigators. Andersson et al. (2006) evaluated different methods of drying biomass in a pulp mill, and found that flue gas dryer was the most attractive. Sosa-Arnao and Nebra (2009) analyzed different energy recovery configurations in boilers fired by bagasse, and showed that the configuration consisting of economizer, air heater, and flue gas dryer had the lowest optimized cost. Li et al. (2012) compared energy saving resulting from the integration of flue gas dryer in a power plant that used pine
chips as fuel and the cost of drying, and concluded that 3 - 4 years of operation was expected to give a return on the investment. Gebreegziabher et al. (2014) proposed a multi-stage process for biomass drying that combines hot air dryer, superheated steam dryer, and flue gas dryer. Liu (2017) determined the limit for the cost of flue gas dryer and the comparison between flue gas dryer and other dryers, none of the previous works have considered the constraint of flue gas dryer installation in presence of economizer and air heater and the optimum installation of these devices.

In this paper, a model of biomass boiler is used to determine the optimum installation of heat recovery devices in biomass boiler. The boiler is required to generate superheated steam at specified flow rate, pressure, and temperature. It is shown that, under the constraint that boiler efficiency is fixed, there are the optimum sizes of economizer, air heater, and flue gas dryer that minimize the total cost of installing these devices.

2. Biomass boiler system

Analysis of a thermal energy system usually requires a boiler model. A widely used model is the black-box model. This model considers only the inputs to the boiler, which are feed water, fuel, and air, and the outputs, which are superheated steam and flue gas. Using this model requires that either boiler efficiency or flue gas temperature is known. Although the black-box model is sufficient in an analysis that does not consider effects of heating surface areas, it is insufficient for the current investigation. A more suitable model must take into account components of the boiler. An illustration of biomass boiler system with flue gas dryer is shown in Fig. 1. Solid lines denote fuel, air, and flue gas, whereas and dashed lines denote feed water and steam. The main components of the system are furnace (F), evaporator (EV), steam drum (SD), superheater (SH), boiler bank (BB), economizer (EC), air heater (AH), and flue gas dryer (FD).

Combustion of fuel in F results in thermal energy that is used to evaporate water in EV and increase steam temperature in SH from the saturated steam temperature \((T_v)\) to \(T_s\). Flue gas leaving F at \(T_g1\) flows successively SH, BB, EC, AH, and FD, and its temperature is reduced, respectively, to \(T_{g2}\), \(T_{g3}\), \(T_{g4}\), \(T_{g5}\), and \(T_{g6}\). Heat transfer from flue gas causes the increase of feed water temperature from \(T_{wi}\) to \(T_{we}\) in EC, the increase of air temperature from \(T_{ai}\) to \(T_{ae}\) in AH, the increase of fuel temperature from \(T_{ai}\) to \(T_f\), and the reduction of fuel moisture content from \(x_{Mi}\) to \(x_{M}\) in FD. Subcooled feed water at a mass flow rate \(m_w\) from EC and saturated steam at mass flow rates \(m_{s1}\) and \(m_{s2}\) from EV and BB enter SD, which returns saturated liquid water at the same mass flow rates to EV and BB, and sends saturated steam at a mass flow rate \(m_s\) to SH. Water evaporation in EV is due to radiative heat transfer from flue gas in F, whereas water evaporation in BB is due to convective heat transfer from flue gas. In order to maintain the concentration of dissolved solids in feed water at a safe level, it is assumed that some of the feed water is blowdown water. It should be noted that, in an actual operation, the inputs to SD from EV and BB are mixtures of saturated steam and saturated liquid water, which are separated in SD. In other words, most saturated liquid water is recirculated through SD. In this simplified model, the recirculated saturated liquid water is ignored, and inputs to SD from EV and BB are assumed to be saturated steam. Mathematical models for F, EV, SD, SH, BB, EC, and AH are provided by Chantasiriwan (2019).
The model of FD is shown in Fig. 2. Assume that fuel is divided into 2 parts with mass fractions $y$ and $(1 – y)$. The mass fraction $y$ of fuel is completely dried in FD, as reported in Eq. (1).

$$
y = \frac{m_f c_{pg} (T_{g6} - T_{g5})}{m_f (1 - x_{Mf}) c_{pg} + x_{Mf} c_{pf} (T_{g6} - T_{g5}) + x_{Mf} c_{pw} (T_{f} - T_{g5}) + \Delta f + c_v (T_{g6} - T_{f})}
$$

where $c_{pg}$, $c_{pf}$, $c_{pw}$, and $c_v$ are specific heat capacities of flue gas, fuel, water, and vapor, $T_f$ is the reference temperature (25°C), and $\Delta f$ is the latent heat of evaporation at the reference temperature. The dried fuel is then mixed with the rest of the fuel. The mass flow rate, the moisture content, and the temperature of fuel at the dryer outlet are determined from Eqs. (2) – (4).

$$
m_f = m_{ff} - y m_{ff} x_{Mf}
$$

$$
x_M = \frac{(1 - y) x_{Mf} m_{ff}}{m_f}
$$

$$
\begin{align*}
& \text{Fuel} \\
& (m_{ff}, x_{Mf}, T_{fi})
\end{align*}
$$

Figure 1. Bagasse boiler model.
\[ T_f = \frac{m_f \left[c_p \left(1 - x_{liq} \right) + \left(1 - y \right) \rho_y + c_p \left(1 - y \right) x_{liq} T_a \right]}{m_f \left[c_p \left(1 - x_{liq} \right) + c_p x_f \right]} \]  \tag{4} 

Figure 2. Flue gas dryer model.

Heating surface areas of F are \( A_f \) and \( A_s \), whereas \( A_{SH}, A_{BB}, A_{EC}, \) and \( A_{AH} \) are, respectively, heating surface areas of SH, BB, EC, and AH. Unlike these heat exchangers, which are characterized by heating surface areas, FD is characterized by the amount of moisture removed from fuel (\( M \)) in kg/h, which is determined from Eq. (5).

\[ M = 3600 \frac{y x_{liq} m_f}{m_f} \]  \tag{5} 

3. Optimization procedure

The 25 primary variables in this boiler system are \( A_f, A_s, A_{SH}, A_{BB}, A_{EC}, A_{AH}, M, p_s, T_a, m_{in}, m_{out}, x_{liq}, x_m, T_{sa}, T_{wa}, T_{wa}, T_{sa}, T_{wb}, T_{gb}, T_{gb}, \) and \( T_{gs} \). The other variables are secondary variables, which may be expressed in terms of primary variables. The system is governed by 12 energy and heat transfer equations. Therefore, the values of 13 primary variables must be specified values so that the solution of the system can be found. Known variables are \( A_f, A_s, A_{SH}, A_{BB}, A_{EC}, A_{AH}, M, p_s, m_{in}, m_{out}, x_{liq}, x_m, T_{sa}, T_{wa}, T_{wa}, \) and \( T_{sa} \) in a boiler system analysis. In a boiler design for the minimum installation cost of heat recovery devices, however, \( A_{EC}, A_{SH}, \) and \( M \) are unknown, and must be determined for given design conditions, which include a fixed value of boiler efficiency. Boiler efficiency (\( \eta \)) is defined in Eq. (6).

\[ \eta = \frac{m_f \left(h_f - h_{fe} \right)}{m_f HHV} \]  \tag{6} 

where \( m_f \) is the mass flow rate of steam, \( h_f \) is the enthalpy of superheated steam at pressure \( p_f \) and temperature \( T_f \), \( h_{fe} \) is the enthalpy of feed water, \( m_f \) is the mass flow rate of fuel, and \( HHV \) is the fuel higher heating value. This design requires the specified values of \( m_f \) and \( T_f \). The other known variables are \( A_f, A_s, A_{BB}, A_{EC}, A_{AH}, M, p_s, m_{in}, m_{out}, x_{liq}, x_m, T_{sa}, \) and \( T_{wa} \). In order to find the minimum installation cost, only \( A_{EC} \) and \( M \) are allowed to vary. As a result, heating surface area \( A_{AH} \) becomes a function of \( A_{EC} \) and \( M \). It is assumed that the nominal unit installation costs of economizer and air heater are, respectively, 120 \$/m², and 100 \$/m². Furthermore, the unit installation cost of flue gas
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Dryer is assumed to be 50 $/(kg/h). Therefore, the total installation cost of heat recovery devices is determined from Eq. (7).

\[ C_{\text{total}} = 120A_{\text{EC}} + 100A_{\text{AH}} + 50M \]  

(7)

The minimum value of \( C_{\text{total}} \) corresponds to the optimum values of \( A_{\text{EC}} \) and \( M \).

4. Results and discussion

The fuel for the boiler system is bagasse of which composition is provided by Rein (2017). The boiler design parameters are \( p_s = 4.5 \) MPa, \( T_s = 500^\circ \text{C} \), and \( m_s = 100 \) kg/s. The fuel moisture content is 52%. The inlet air and fuel temperatures are 30°C. The inlet feed water temperature is 120°C.

By fixing \( \eta \) at 70%, it is found that \( A_{\text{AH}} \) decreases as either \( A_{\text{EC}} \) or \( M \) increases. Furthermore, \( C_{\text{total}} \) varies with only \( A_{\text{EC}} \) and \( M \). The minimum value of \( C_{\text{total}} \) may be found by using a line-search method. First, the optimum value of \( A_{\text{EC}} \) that yields the minimum installation cost at a specified value of \( M \) \( (C_{\text{min},M}) \) is determined. Figure 3 shows variations of \( C_{\text{total}} \) with \( A_{\text{EC}} \) for four values of \( M \). \( C_{\text{min},M} \) is found to be $1.144 \times 10^6$, $1.128 \times 10^6$, $1.124 \times 10^6$, and $1.132 \times 10^6$ for \( M = 0, 2000, 4000, \) and 6000 kg/h, respectively. Next, \( C_{\text{min},M} \) is plotted as a function of \( M \) as shown in Fig. 4. It can be seen that the minimum installation cost \( (C_{\text{min}}) \) of $1.125 \times 10^6$ results from the optimum value of 3550 kg/h for \( M \). The corresponding values of \( A_{\text{EC}} \) and \( A_{\text{AH}} \) are, respectively, 4685 m² and 3844 m³. Therefore, the installation of flue gas dryer in addition to economizer and air heater results in 1.7% less total installation cost than the installation of only economizer and air heater. It should be noted that this result is obtained for the value of 50 $/(kg/h)$ for the unit cost of flue gas dryer. The minimum installation cost is quite sensitive to the unit cost of flue gas dryer. When the unit cost reaches 61 $/(kg/h)$, the installation of flue gas dryer is not justified because \( C_{\text{min}} \) is equal to \( C_{\text{min},0} \), and the installation of flue gas dryer increases the total installation cost.

![Figure 3](image-url)

Figure 3. Variations of total installation cost \( (C_{\text{total}}) \) with the economizer surface area \( (A_{\text{EC}}) \) and the amount of removed moisture \( (M) \).
Figure 4. Variation of minimum installation cost at a fixed $M$ value ($C_{\text{min},M}$) with $M$.

5. Conclusion

Three heat recovery devices that may be installed in a biomass boiler are economizer, air heater, and flue gas dryer. They decrease flue gas temperature, and increase boiler efficiency. Since all three devices require thermal energy from high-temperature flue gas that results from combustion of biomass fuel, there are limits to the sizes of these devices under given boiler operating conditions if they are installed together. For a fixed value of 70% for the boiler efficiency, a boiler model can be used to demonstrate that there are the optimum sizes of these devices that result in the minimum installation cost. Simulation results indicate that the optimum installation of economizer, air heater, and flue gas dryer can reduce the installation cost by 1.7% compared with a non-optimum installation, in which there are only economizer and air heater. Cost reduction increases with decreasing unit cost of dryer.

References

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