The research on the influence of boiler operating parameters on thermal efficiency

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Abstract. The influence of operating parameters on thermal efficiency was analyzed by thermal balance experiment of the boiler. The mathematical model of thermal efficiency was obtained by thermal balance equation. The results showed that the thermal efficiency decreased with the increase of exhaust gas temperature. The excess air coefficient had an important effect on thermal efficiency of the boiler. The thermal efficiency decreased with the increase of excess air coefficient. The increase of inlet air temperature led to the increase of thermal efficiency when other operating parameters remained unchanged. The thermal efficiency increased with the increase of fuel calorific value. As a result, in order to improve thermal efficiency, the optimum excess air coefficient should be adjusted as much as possible to ensure combustion condition of the boiler. For running boiler, the economizer should be installed on heated surface at the end of boiler.

1. Introduction
Energy is the foundation of national economic development. In recent years industrial boiler has developed steadily. At present, there are 600,000 industrial boilers in China. Every year 500 million tons of standard coal is consumed by industrial boilers, accounted for about a quarter of the total coal production[1]. The designed thermal efficiency of industrial boiler in China is between 72% and 80%. The average operating efficiency of industrial boiler is mostly between 60% and 70%, which is 10% below the designed thermal efficiency[2]. Especially for the coal-fired boilers, energy waste is quite serious[3]. There are many reasons for serious energy waste of boilers. The design of boiler is not idea. The average evaporation of running boiler is less than 65%. The equipment is not updated in many years. The automatic control level of equipment is low. The type of fuel used is not consistent with the type of fuel designed. The management and supervision of boiler energy saving is lacked, and so on[4].

There are many factors that affect thermal efficiency of the boiler. The thermal efficiency can be calculated according to the method of inverse balance analysis. The heat loss of boiler is mainly composed of the heat loss from exhaust gas, the heat loss from gas incomplete combustion, the heat loss from solid incomplete combustion, the surface heat loss and the heat loss from coal slag and ash[5]. The main operating parameters affecting thermal efficiency are the temperature of exhaust gas, excess air coefficient, the temperature of feed water, the temperature of inlet air, and so on. It is very important to research the influence of operating parameters on thermal efficiency.

2. Mathematical model of thermal efficiency
In the thermal balance test, the heat loss of the boiler is calculated by the experimental data. According to the method of inverse balance analysis, the thermal efficiency can be calculated.
The boiler thermal efficiency is the percentage of the effective utilization heat to the input heat[6]. There are two methods of thermal balance test, which is positive balance test and inverse balance test. The thermal efficiency of boiler is calculated by thermal balance equation

\[ \eta = 100 - (q_2 + q_3 + q_4 + q_5 + q_6) \]  

where \( \eta \) is the thermal efficiency of boiler. \( q_2 \) is the heat loss from exhaust gas. \( q_3 \) is the heat loss from gas incomplete combustion. \( q_4 \) is the heat loss from solid incomplete combustion. \( q_5 \) is the surface heat loss. \( q_6 \) is the heat loss from coal slag and ash.

The heat loss from exhaust gas exists because the heat is taken away by exhaust gas. The main heat loss of boiler is the heat loss from exhaust gas. The heat loss from exhaust gas \( q_2 \) is obtained from

\[ q_2 = \frac{K_{q4}}{Q_r} (h_{py} - h_{lk}) \times 100 \]  

where \( K_{q4} \) is correction factor. \( Q_r \) is the total heat into the boiler. \( h_{py} \) is the enthalpy of exhaust gas. \( h_{lk} \) is the enthalpy of air into the furnace.

There is a part of combustible gas in the exhaust gas, which causes the heat loss from gas incomplete combustion. The heat loss from gas incomplete combustion \( q_3 \) is calculated by the formula

\[ q_3 = \frac{V_5 \times K_{q4}}{Q_r} (126.36CO + 107.98H_2 + 358.18C_mH_n) \times 100 \]  

where \( V_5 \) is the volume of dry flue gas. \( CO, H_2, C_mH_n \) are \( CO, H_2, C_mH_n \) in the component content of exhaust gas, respectively.

The heat loss from solid incomplete combustion is the main heat loss of coal-fired boiler. The reason is that combustible component of coal slag and ash is not burned completely[7]. The heat loss from solid incomplete combustion \( q_4 \) is obtained from

\[ q_4 = \left( \frac{\alpha_{lz} \times C_{lz}}{100 - C_{lz}} + \frac{\alpha_{im} \times C_{im}}{100 - C_{im}} + \frac{\alpha_{fh} \times C_{fh}}{100 - C_{fh}} \right) \times 328.664A_{ar} \]  

where \( \alpha_{lz}, \alpha_{im} \) and \( \alpha_{fh} \) are the percentage of coal slag, coal leakage and fly ash in the total amount of coal ash, respectively. \( C_{lz}, C_{im} \) and \( C_{fh} \) are the combustible content of coal slag, coal leakage and fly ash, respectively. \( A_{ar} \) is the ash content of the coal as received basis.

The surface heat loss exists because the temperature of the boiler surface is higher than the ambient temperature. The surface heat loss \( q_5 \) is calculated by the formula

\[ q_5 = \frac{1670F}{BQ_r} \times 100\% \]  

where \( F \) is the heat dissipation surface area of boiler. \( B \) is the consumption of fuel into the boiler.

The heat loss from coal slag and ash exists because physical sensible heat is carried by ash and slag discharged from boiler. The heat loss from coal slag and ash \( q_6 \) is obtained from

\[ q_6 = \frac{A_{ar} \times (ct)_{lz}}{Q_r \times (100 - C_{lz})} + \frac{A_{ar} \times (ct)_{im}}{100 - C_{im}} \]  

where \( (ct)_{lz} \) is the enthalpy of coal slag. \( (ct)_{im} \) is the enthalpy of coal leakage.

Under different operating conditions, the various heat losses of the boiler could be obtained by mathematical model of thermal efficiency[8]. According to the research on the influence of operating parameters, the effective ways could be obtained to improve the thermal efficiency and the operating conditions of the boiler. The heat loss and energy waste could be avoided.

3. The influence of operating parameters on thermal efficiency

According to the mathematical model of thermal efficiency, the main operating parameters affecting thermal efficiency are the temperature of exhaust gas, excess air coefficient, the temperature of feed water, the temperature of inlet air, and so on. It is very important to research the influence of boiler
operating parameters on thermal efficiency. In thermal balance experiment, the main operating parameters of boiler were shown in Table 1.

### Table 1. Operating parameters of the boiler in thermal balance experiment

| Operating parameter                  | Value       |
|--------------------------------------|-------------|
| Steam flow / (kg/h)                 | 6000        |
| Steam pressure / MPa                | 1.25        |
| Feed water temperature / °C         | 20          |
| Feed water pressure / MPa           | 1.3         |
| Inlet air temperature / °C          | -15～+35     |
| Exhaust gas temperature / °C        | 70～100      |
| Excess air coefficient              | 1.2～3.0     |
| Fuel calorific value / (MJ/kg)      | 10.0～32.0   |

3.1. The influence of exhaust gas temperature on thermal efficiency

Figure 1 showed the influence of exhaust gas temperature on thermal efficiency under different excess air coefficient. When the excess air coefficient was constant, thermal efficiency decreased with the increase of exhaust gas temperature. The lower the excess air coefficient, the higher the thermal efficiency. When the air coefficient $\alpha_{py}$ is 1.4, the thermal efficiency decreased about 1.06% when exhaust gas temperature increased by 20°C. When the air coefficient $\alpha_{py}$ is 1.6, the thermal efficiency decreased about 1.20% when exhaust gas temperature increased by 20°C. When the air coefficient $\alpha_{py}$ is 1.8, the thermal efficiency decreased about 1.34% when exhaust gas temperature increased by 20°C.

The reasons for the high temperature of exhaust gas are as follows. The waste heat utilization equipment is not installed on heated surface at the end of boiler. The type of fuel used is inconsistent with the type of fuel designed. The combustion condition of boiler is not ideal, and so on. The heat loss from exhaust gas mainly depends on the exhaust gas temperature. The increase of exhaust gas temperature leaded to the increase of heat loss from exhaust gas. Therefore, the economizer should be installed on heated surface at the end of boiler in order to improve thermal efficiency.
3.2. The influence of excess air coefficient on thermal efficiency

![Figure 2. The relation between excess air coefficient and thermal efficiency](image)

The relationship between excess air coefficient and thermal efficiency under different exhaust gas temperature was shown in Figure 2. When the exhaust gas temperature was constant, thermal efficiency decreased with the increase of excess air coefficient. The lower the exhaust gas temperature, the higher the thermal efficiency. When the exhaust gas temperature \( t_{pg} \) is 140°C, the thermal efficiency decreased about 0.81% when excess air coefficient increased by 0.2. When the exhaust gas temperature \( t_{pg} \) is 160°C, the thermal efficiency decreased about 0.95% when excess air coefficient increased by 0.2. When the exhaust gas temperature \( t_{pg} \) is 180°C, the thermal efficiency decreased about 1.09% when excess air coefficient increased by 0.2.

The excess air coefficient has an important effect on thermal efficiency of the boiler. The higher the excess air coefficient, the greater the heat loss from exhaust gas. Unreasonable distribution of the air in boiler furnace caused the excess air coefficient to increase. The combustion condition of boiler furnace was very poor when excess air coefficient was not controlled properly. The increase of flue gas volume leaded to the increase of heat loss from exhaust gas. Heat loss from gas incomplete combustion increased because of the poor combustion condition of boiler furnace.

3.3. The influence of inlet air temperature on thermal efficiency

![Figure 3. The relation between inlet air temperature and thermal efficiency](image)

The influence of inlet air temperature on thermal efficiency was shown in Figure 3. When other operating parameters were constant, thermal efficiency increased with the increase of inlet air temperature. The thermal efficiency increased about 0.3% when inlet air temperature increased by 5°C. The increase of inlet air temperature leaded to the increase of heat brought into the boiler by inlet air. Heat loss from exhaust gas decreased because of the increase of inlet air temperature.
3.4. The influence of fuel calorific value on thermal efficiency

Figure 4 showed the influence of fuel calorific value on thermal efficiency. It was obvious from Figure 4 that the increase of fuel calorific value leaded to the increase of thermal efficiency. The thermal efficiency increased 1.85% when the fuel calorific value increased 2.09 MJ/kg.

At present the layer combustion is the main combustion mode of coal-fired boiler. In China the type of fuel used is often inconsistent with the type of fuel designed. When the fuel is changed, the fuel is not suitable for the structure of boiler furnace. Compared with the designed condition, the combustion condition of the boiler is affected. In general, the combustion condition of the boiler is worse when the fuel is changed. The thermal efficiency is affected by the quality of fuel. The calorific value of the fuel has an important influence on the carbon content of the slag. The heat loss from solid incomplete combustion decreased with the increase of calorific value. As a result, the thermal efficiency of boiler increased with the increase of calorific value.

The important reasons that thermal efficiency of coal-fired boiler is generally lower than the designed efficiency are as follows. The type of fuel used is inconsistent with the type of fuel designed. Compared with the designed condition, the combustion condition of the boiler is worse. Therefore, in order to improve thermal efficiency of boiler, the type of fuel used should be consistent with the type of fuel designed as much as possible.

4. Conclusions

In this paper the influence of boiler operating parameters on thermal efficiency was analyzed. According to the method of inverse balance analysis, the thermal efficiency can be calculated. The results showed that the thermal efficiency decreased with the increase of exhaust gas temperature. When the air coefficient $\alpha_{py}$ is 1.4, the thermal efficiency decreased about 1.06% when exhaust gas temperature increased by 20°C. The thermal efficiency decreased with the increase of excess air coefficient. When the exhaust gas temperature $t_{py}$ is 160°C, the thermal efficiency decreased about 0.95% when excess air coefficient increased by 0.2. The increase of inlet air temperature leaded to the increase of thermal efficiency when other operating parameters remained unchanged. The thermal efficiency increased about 0.3% when inlet air temperature increased by 5°C. The thermal efficiency increased 1.85% when the fuel calorific value increased 2.09 MJ/kg.

According to the research, the effective ways could be obtained to improve the operating conditions and the thermal efficiency of the boiler. It was the most effective way to decrease exhaust gas temperature in order to improve thermal efficiency. For running boiler, the economizer should be installed on heated surface at the end of boiler. In addition, excess air coefficient had an important effect on thermal efficiency of the boiler. The optimum excess air coefficient should be adjusted as much as possible to ensure combustion condition of the boiler.
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