Energy conservation certification for coal layer-combustion industrial boiler

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Abstract. The effect of boiler load on main operation parameters and the boiler efficiency were investigated, and the thermal efficiency distribution of nearly 300 coal-fired boilers was further analyzed. The results show that the exit gas temperature decreases as the boiler load decreases, while the unburned carbon contents in ash and slag, and CO content in flue gas usually increase. Correspondingly, the loss due to exit gas decreases, and the loss due to unburned solids usually increases. The loss due to surface radiation and convection increases. Taking into account changes of all the losses, the boiler efficiency decreases at lower loads. With reference to TSG G0002, Technical Specification for Energy Conservation Certification of Coal Layer-Combustion Industrial Boiler under off-Design Conditions has been drafted and the evaluating values of energy conservation for products have been proposed, including boiler efficiency under different test loads and CO concentration in flue gas. The target efficiency values vary according to the boiler capacity and fuel type. The CO concentration value is a limit that can be achieved by most boilers.

1. Introduction

There are more than 400,000 industrial boilers in China, most of which are coal-fired boilers. Industrial boilers are widely used for steam production in various industries and building heating in northern regions. According to different combustion modes, coal-fired industrial boilers can be further divided into layer combustion boilers, fluidized bed boilers and pulverized coal boilers, among which the layer-combustion boiler is the most widely used type.

In recent years, with the improvement of design and manufacturing level of industrial boilers, and the elimination of small-capacity coal-fired boilers year by year, the overall energy efficiency level of coal-fired industrial boilers has been increased. In 2016, the Supervision Administration Regulation on Energy Conservation Technology for Boiler (TSG G0002-2010) stipulates that the thermal efficiency target values of layer-combustion boilers with different capacities and different coal types under the rated condition are all higher than 85%, and the limit values higher than 80%[1]. However, the actual efficiency during daily operation is much lower[2]. And it is a very common phenomenon that industrial boilers operate under non-rated conditions. Therefore, improving the energy efficiency level of coal-fired industrial boilers under variable working conditions is of great significance for promoting boiler energy conservation and emission reduction. B X Zhang proposed an optimization design of the control system for low load operation of coal-fired chain furnace, and determined the boiler parameters suitable for low load operation[3]. The economic operation under low load can be achieved by coal layer thickness and grate speed optimization[4]. M Tontu conducted performance analysis of a coal-fired steam power plant with varying loads[5].
The Chinese regulations and standards have specified the energy efficiency indexes of industrial boilers under rated conditions and industrial boiler systems[6]. The energy efficiency index in Japan specifies the excess air coefficient for a certain load range. The EU code considers the weighting efficiency of different loads and the US Energy Star examines the annual fuel utilization efficiency. In general, the thermal efficiency indexes for industrial boilers under variable working conditions have not yet been seen in the literature.

The effect of boiler load on exit gas temperature, CO content in flue gas and unburned carbon loss was investigated by field tests in this work. The thermal efficiency distribution of nearly 300 coal-fired boilers was analyzed. Based on the above analysis, with reference to TSG G0002, the energy conservation certification technical specification for coal layer-combustion industrial boiler under off-design conditions was developed.

2. Principles and methods of boiler efficiency test

2.1 Efficiency calculation

The basis of thermal efficiency calculation is the first law of thermodynamics, namely the law of conservation of energy. It can be stated as

\[
Q_rF (\text{Input from fuel}) + Q_rB (\text{Credits}) = Q_rO (\text{Output}) + Q_rL (\text{Losses})
\]  

(1)

According to GB/T 10180, the boiler efficiency is calculated as equation (2), which is a typical formula of gross efficiency.

\[
\eta = 100 \times \frac{Q_rO}{Q_rF + Q_rB} (\%) 
\]

(2)

Combining equation (1) and equation (2), equation (3) can be obtained,

\[
\eta = \left[ 100 - 100 \times \frac{Q_rL}{Q_rF + Q_rB} \right] (\%)
\]

(3)

which can be further expressed as:

\[
\eta = \left[ 100 - (q_2 + q_3 + q_4 + q_5 + q_6 + q_7) \right] (\%)
\]

(4)

where

- \(q_2\) -- loss due to flue gas, %;
- \(q_3\) -- loss due to unburned gases, %;
- \(q_4\) -- loss due to unburned solids, %;
- \(q_5\) -- loss due to surface radiation and convection, %;
- \(q_6\) -- loss due to sensible heat of residue, %;
- \(q_7\) -- loss due to sulfur capture, %.

2.2 Testing methods

During the test, coal and slag were sampled, exhaust gas composition was analyzed and main operating parameters were recorded. Coal sampling timing should be advanced properly according to the time for fuel from the sampling point to the furnace to ensure that the sample is representative. Exhaust gas was sampled at the gas duct outlets of the air heaters. The content of each flue gas component was measured by using a multi-component flue gas analyzer.

Main operating parameters were recorded once every 5 or 15 minutes. The averages of the following parameters during the entire test period were taken: outlet water temperature and pressure, feed water flow, temperature and pressure, air temperature and exhaust gas temperature, etc.
3. Field test results
In order to study the impact of load changes on boiler operation, hot water boilers with capacities of 58MW and 29MW were tested in Changchun, Mudanjiang and some other cities. Exit gas temperature is one of the most important factors affecting boiler efficiency, which determines the sensible heat loss due to flue gas together with the flue gas flow. The change in flue gas temperature with boiler load is shown in figure 1. It can be seen that the exit gas temperature decreases as the boiler load decreases, mainly caused by decrease in furnace temperature.

The unburned carbon content reflects the combustion status of the boiler. The change in unburned carbon content with boiler load is shown in figure 2. The furnace temperature is lower under lower boiler load. The combustion intensity decreases, usually leading to higher carbon content in ash or slag. But there are some other factors affecting combustion. For instance, in many cases, the excess air ratio will be increased properly at lower load to ensure coal particles burning-out. Therefore, the change trend is usually complicated. Another indicator that reflects the combustion status is CO content in flue gas. Generally, CO content increases at lower boiler load. But increasing the excess air ratio has a diluting effect, leading to decrease in CO content.

The efficiency test and calculation results of a 58 MW boiler in Changchun are shown in table 1 and figure 4. It can be clearly seen that the boiler efficiency decreases as the load decreases. The loss due to exit gas can be calculated using equation (5). It means that the loss due to exit gas will decrease if the excess air ratio remains constant. $K_{q_1}$ is the correction factor, which can be calculated by...
As the boiler load decreases, the loss due to unburned solids usually increases, as shown in figure 4, leading to decrease in $K_{q4}$.

$$q_4 = \frac{K_{q4}}{Q_{in}}(h_{in} - h_{ca}) \times 100$$

where $Q_{in}$ is the energy entering the system, $h_{in}$ is the exit gas enthalpy, and $h_{ca}$ is the cold air enthalpy.

$$K_{q4} = \frac{100 - q_4}{100}$$

The loss due to surface radiation and convection increases as the boiler load decreases. The temperature change on the outer surface under different loads is relatively small, which means that the heat exchange due to surface radiation and convection almost remains constant. The input energy decreases at lower load, so the ratio of heat exchange due to surface radiation and convection to input energy increases. Taking into account changes of all the losses, the boiler efficiency decreases at lower loads.

### Table 1. Test results of a 58 MW boiler in Changchun

| Item                        | Unit | Case 100% | Case 70% | Case 50% |
|-----------------------------|------|-----------|----------|----------|
| Boiler output               | MW   | 56.57     | 41.04    | 29.39    |
| Boiler efficiency           | %    | 84.72     | 83.52    | 80.01    |
| Exit gas temperature        | ºC   | 138.70    | 132.18   | 117.50   |
| Excess air ratio            | /    | 1.43      | 1.81     | 1.52     |
| Loss due to flue gas        | %    | 7.99      | 7.47     | 5.54     |
| Loss due to unburned gases  | %    | 0.013     | 0.027    | 0.021    |
| Loss due to unburned solids | %    | 6.07      | 7.35     | 12.16    |
| Loss due to surface radiation and convection | % | 0.8       | 1.14     | 1.6      |
| Loss due to sensible heat of residue | % | 0.41      | 0.49     | 0.67     |

Figure 4. Boiler efficiency of a 58 MW boiler in Changchun.

### 4. Platform data analysis

A large number of boiler efficiency test data have been accumulated in “Industrial boiler efficiency test data calculation and management platform”. The boiler efficiency distribution, exit gas temperature, excess air ratio and CO concentration of different coal type boilers under different test loads were analyzed. The results show that with the decrease in test load, the boiler efficiency shows a downward trend, the exit gas temperature decreases and the excess air ratio increases. The thermal
efficiency distributions of coal-fired industrial boilers with different capacities are shown in figure 5 and figure 6. The statistical results of CO concentration are shown in figure 7. It can be seen that the distribution is dispersed, but most of the data are below 200ppm.

![Figure 5. Efficiency distribution (Rated capacity>20t/h)](image1)
![Figure 6. Efficiency distribution (≤20t/h)](image2)
![Figure 7. CO concentration in flue gas](image3)

5. Evaluating values of energy conservation

Based on the field test results and platform data statistics, Technical Specification for Energy Conservation Certification of Coal Layer-Combustion Industrial Boiler under off-Design Conditions has been drafted and the evaluating values of energy conservation for products have been proposed, as shown in table 2. The evaluating values of energy conservation include boiler efficiency and CO concentration. The boiler efficiency is the most intuitive indicator of energy conservation level. The target values vary according to the boiler capacity and fuel type. Three typical loads are chosen as the test loads, namely, 100%, 70% and 50%. The target values under the 100% load are consistent with TSG G0002. The CO concentration can well reflect the combustion situation of the boiler. On the one hand, reducing the CO concentration will help the boiler to improve the thermal efficiency. On the other hand, the CO index will help to avoid the phenomenon that the fuel efficiency is sacrificed to achieve pollutant emission reduction. The CO concentration limit value is a necessary condition to achieve energy conservation, which is the limit that can be achieved by most boilers.
Table 2. Evaluating values of energy conservation

| Item            | Fuel type  | Lower heating value $Q_{\text{net,v.ar}}$ (KJ/kg) | Rated capacity $D \leq 20$ t/h or $Q \leq 14$ MW Load | Rated capacity $D > 20$ t/h or $Q > 14$ MW Load |
|-----------------|------------|---------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Boiler efficiency (%) | Bituminous coal | II $17700 \leq Q_{\text{net,v.ar}} \leq 21000$ | 85 83 80 86 84 81 | 100% 70% 50% 100% 70% 50% |
|                 |            | III $Q_{\text{net,v.ar}} > 21000$ | 87 84 82 89 86 84 |                                                  |
|                 | Lignite    | $Q_{\text{net,v.ar}} \geq 11500$ | 85 83 80 87 85 82 | 200                                              |

6. Conclusions

The effect of boiler load on main operation parameters and the boiler efficiency were investigated. The exit gas temperature decreases as the boiler load decreases, while the unburned carbon contents in ash and slag, and CO content in flue gas usually increase. Correspondingly, the loss due to exit gas decreases, and the loss due to unburned solids usually increases. The loss due to surface radiation and convection increases at lower load. Taking into account changes of all the losses, the boiler efficiency decreases at lower loads. The thermal efficiency distribution of nearly 300 coal-fired boilers was further analyzed. With reference to TSG G0002, the evaluating values of energy conservation for products were proposed, including boiler efficiency under different test loads and CO concentration in flue gas. The target efficiency values vary according to the boiler capacity and fuel type. The CO concentration limit value is a necessary condition to achieve energy conservation, which is the limit that can be achieved by most boilers.

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