Design-Based Thermal Efficiency Correction Method for Hot Water Boiler

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Abstract: In the boiler design process, the thermal efficiency of the boiler operating under specified parameters is given in accordance with the design specifications. However, under the actual operating conditions, the specified parameters in the design book cannot be met at the same time. Especially for the hot water boiler, the coal quality component and the deviation of low calorific power, the feed water temperature and the ambient temperature will directly affect the operating efficiency of the boiler. In the current boiler energy efficiency test standards, the test conditions are very demanding. It is required to be the design coal type and it also gives fluctuation ranges for several parameters that affect the boiler operation efficiency. For non-design conditions, the boiler operation condition test method can only be executed referring to the standard. However, the measured efficiency is highly variable. This paper aims to analyze and study several parameters affecting boiler efficiency based on the perspective of boiler design, and give corresponding efficiency correction method to provide reference for the correction of energy efficiency test results under non-design conditions.

1. Introduction

"Hot water boiler" refers to a boiler that uses various fuels to convert chemical energy into heat energy and outputs it in the form of hot water. This type of boiler is used as a heating boiler mainly in the "three north" areas, namely northeast, north and northwest. According to incomplete statistics, there were about 2,000 hot water boilers in Liaoning Province at the end of 2018. In recent years, with the adjustment of industrial structure and environmental protection requirements, hot water boilers have developed towards large capacity and high parameters. From 2015, Liaoning Province eliminated a total of 2,000 small coal-fired boilers, most of which were small-scale regional heating boilers. From 2016, 10/t and below coal-fired small boilers were eliminated, and new coal-fired boilers of 20t/h and below were prohibited. In particular, at the end of 2017, 10 ministries and commissions such as the National Development and Reform Commission and the National Energy Administration issued the "Northern District Winter Clean Heating Plan (2017-2021)", clearly stated that "in 2021, all urban areas will realize clean heating, all coal-fired boilers below 35 steam tons be dismantled; the clean heating rate of the county and urban-rural junctions reached over 80%, and the coal-fired boilers below 20 steam tons be dismantled, and the clean heating rate in rural areas reach over 60%". At the same time, amount requirement of ultra-low emission was proposed for the unremoved boilers (under the condition of 6% oxygen content, the emission concentration of soot, sulfur dioxide and nitrogen oxides should be not higher than 10, 35, 50 mg/ m³ respectively). Under the double impact of industry and environmental
protection requirements, the average single-unit capacity of the hot water boiler in Liaoning Province has been increased from the previous 8.7MW to 25.6MW, and only one or several large heating boiler rooms in the urban built-up area which have a heating radius of 50-100km. For some townships and industrial and mining enterprises with relatively low population and low heat demand, some small hot water boilers are reserved.

Thermal efficiency is the main indicator\(^1\) of boiler thermal performance. It is directly related to the operating cost of hot water boilers. For heating units, fuel cost accounts for more than 70% of the total operating cost. To this end, heating companies generally use the method of monitoring the main thermal parameters of the boiler to indirectly calculate the boiler operating efficiency and achieve the assessment of the boiler room management level and the furnacemen’s capacity.

The Test Procedure for Thermal Performance of Industrial Boilers (GB/T10180-2017) gives the test and conversion method for boiler thermal load and operating thermal efficiency under full load operation conditions. In the actual operation of the boiler, it is necessary to calculate the downstream heat consumption according to factors such as the ambient temperature and the heating area to determine the load of the operation, so that the current standard has great limitations. In the initial design of the boiler, the radiation in the furnace and the convection heating surface are designed according to the rated load of the boiler. When the boiler load drops, due to the innate design, the heating surface of the boiler will not automatically increase or decrease according to the operating load. In this condition, the design thermal efficiency of the boiler will change accordingly. It is obviously biased to evaluate the boiler energy efficiency level under non-rated operating conditions based on the thermal efficiency index under full load conditions. Therefore, it is necessary to propose a boiler energy efficiency test method suitable for different working conditions and different operating parameters, and the corresponding calculation method, that the natural defects in the existing standards can be solved scientifically an objectively.

2. Calculation Method and Model Introduction
This method attempts to follow the QXL46-1.25-70/115-AII boiler designed by a boiler plant to ensure that the boiler structure, heating area, medium and flue gas flow rate are constant, and only changes several important index parameters affecting the thermal efficiency of the boiler to obtain the influence curve of the value change on the boiler’s thermal efficiency, and give the correction coefficient correcting back to the original design parameters.

Refer to the correction method on net power of ASME PTC46-1996 for the overall performance test standard of power plants. Considering the above factors have a direct impact on energy efficiency, the multiplication correction method\(^2\) is adopted for this purpose. The calculation formula is as follows:

\[
\eta_r = \eta \prod_{i=0}^{4} \alpha_i
\]

Of which:
- \(\eta\) - conversion thermal efficiency, %;
- \(\eta\) - test thermal efficiency, %;
- \(\alpha_1\) - correction of fuel calorific value;
- \(\alpha_2\) - correction of ambient temperature;
- \(\alpha_3\) - correction of feed water temperature deviation;
- \(\alpha_4\) - correction of output heat.

3. Calculation Results and Discussion

3.1 Correction of Low Calorific Value of Fuel
The input heat has a great influence on the thermal efficiency of the boiler. The input heat\(^3\) of the general hot water boiler mainly includes: fuel heat, physical sensible heat of fuel, external heating fuel or air heat, self-use steam heat and fuel oil atomizing steam heat. Among them, fuel heat is the mainstay,
accounting for more than 90% of the total input heat. In the traditional boiler thermal efficiency calculation method, fuel heat is the product of the fuel low heat value and the fuel amount. For oil and gas boilers, the composition’s consistency is high and the calorific value is stable, but the calorific value is related to the ratio of hydrogen content. The higher the proportion of hydrogen, the higher the calorific value. Compared with gas and liquid fuels, solid fuel components have poor consistency and unstable calorific value. Taking coal as an example, the main elements in coal that react with oxygen and release heat are carbon, hydrogen and sulfur. Hydrogen and sulfur are mainly concentrated in the volatile matter of coal, while the low calorific value of coal needs to deduct the heat released by the combustion of some hydrogen and all sulfur. The hydrogen content in coal is small, so it can be simply considered that the low calorific value of coal depends mainly on the carbon content. After the fuels of same quality are sent into the boiler, the coal with high carbon content generates greater amount of heat, which results in a higher furnace heat volume. According to the Stephen Boltzmann formula, it can be calculated that it has larger amount of heat exchange with the radiation heating surface in the furnace. The heat exchange of the medium is enhanced, thereby the operating efficiency of the boiler is improved.

After the coal particles enter the boiler, they are heated in the furnace. After the water is evaporated and volatilized, the porous medium structure will be formed. This will facilitate the penetration of oxygen into the core of the coal particles and react with the carbon elements. The heat generated by the reaction softens the coal particles. Meanwhile, the carbon dioxide gas is generated and overflows, and the carbon particles are broken to complete the condensation reaction⁴. After the coal particles break, the particle size decreases and the specific surface area increases, which is beneficial to the carbon particles to further react with oxygen, and the carbon particles are burned out. When the coal ash contains an alkali metal element compound, it will be melted and will be wrapped on the surface of the particle after being heated, which will hinder the carbon and oxygen from further reacting, resulting in excessive carbon content of the slag or fly ash, and the combustion efficiency is lowered. From the industrial analysis point of coal, the sum of the components is 100%, the higher the ash content, and the lower the carbon content, then the smaller the calorific value will be.

The low calorific value of the original designed coal of the boiler is 17693kJ/kg. Calculate the boiler thermal efficiency corresponding to several typical coal types in the second type bituminous coal interval. The efficiency curve shown in Figure 1 is obtained. The abscissa is the dimensionless quantity. It is the ratio of the low calorific value of fuel coal to the low calorific value of the designed coal.

![Figure1. Correction of Boiler Heat Efficiency to Boiler Thermal Efficiency](image)

Fit the curve and get the formula (ii):

$$\alpha_t = -7 \times 10^{-6} x + 1.1301$$  \( (2) \)

3.2 Correction of Ambient Temperature

The ambient temperature only affects the heat loss and the supply air temperature of the boiler. In the case of the same type of coal, the furnace temperature is basically the same, and after the heat is absorbed
by the heating surface, part of the heat is transferred to the furnace wall, so that the furnace temperature is basically the same. Because of the combustion in the furnace, the internal heat source is formed, the temperature of the furnace wall must be higher than the ambient temperature. When the ambient temperature is high, the temperature difference between the furnace wall and the surrounding environment is small, From the convective heat transfer formula (iii), when the coefficient is constant, the smaller the temperature difference is, the smaller the heat exchange amount is, that is, the smaller the heat loss is, the greater the thermal efficiency of the boiler is.

\[ q = h \times \Delta t \]  

(3)

Of which:  
- \( q \) - heat flux density, \( W / m^2 \);
- \( h \) - convective heat transfer coefficient, \( W / (m^2 \cdot ^\circ C) \);
- \( \Delta t \) - temperature difference, \(^\circ C\).

The inlet of the hot water boiler’s air blower is generally set in the boiler room, and the supply air temperature is equivalent to the ambient temperature. When the ambient temperature is low, a large amount of heat is generated in the furnace due to the combustion of coal particles. The low-temperature air will absorb a large amount of heat and finally form a high-temperature flue gas, and the heating surface of the furnace will complete the entire heat exchange process; and for the high temperature environment, the air absorbs less heat, and then the combustion efficiency is increased. In order to improve boiler design efficiency, some boiler manufacturers generally set a preheater at the tail of the boiler and use high-temperature flue gas to heat the boiler air supply. This is the same principle.

Using the same method, the effect of ambient temperature change on boiler thermal efficiency is shown in Figure 2.

![Figure 2. Correction of Boiler Thermal Efficiency by Ambient Temperature](image)

Fit the curve to get the formula (iv):

\[ \alpha_2 = -0.0004x + 1 \]  

(4)

3.3 Correction of Feed Water Temperature Deviation

The Parameters for Hot Water Boiler (GB/T 3166-2004) gives four series of rated inlet and outlet water temperatures of 46 MW boiler, which are 115/70, 130/70, 150/90 and 180/110. For the heating pipe network, when the pressure in the local area is lower than the partial pressure of the saturated water, the saturated water will be vaporized to generate steam in a large amount, resulting in uneven distribution of heat in the pipe network, the heat balance of the pipe network cannot be achieved. There will be too much steam generated and will form a pipe network water hammer, seriously affecting the safety of the pipe network. Therefore, the current standards have been seriously divorced from reality and cannot serve as technical guidance. At present, the 46MW boiler operated by the heating company generally adopts the method of low temperature supply, that is, under the premise of ensuring the temperature
difference, the effluent’s temperature is lowered below the boiling point of water to ensure the safety of the pipe network.

Considering the heat exchange between the working medium side and the flue gas side, it can be known that more heat exchange amount because of larger temperature difference. Therefore, under the premise of ensuring that the heat capacity of the hot water boiler is constant, that is, the temperature difference and the flow rate are the same, refer to the operating parameters of the hot water boiler, calculate the typical boiler feed water temperature downward based on 70 °C, and calculate the boiler operating efficiency, then the Figure 3 is obtained. The abscissa is the dimensionless amount, which is the ratio of the feed water temperature to 70 °C.

![Figure 3](image-url)

Figure 3. Boiler Efficiency Correction Caused by Water Temperature Deviation

Fit and get the formula (V):

$$\alpha_3 = 0.0251x + 0.9748$$  \hspace{1cm} (5)

3.4 Correction of Heat Output of Hot Water Boiler (Including Boiler Feed Water Temperature Difference and Flow Rate)

Figure 4 shows the efficiency indexes of the boiler under different inlet and outlet water temperature and circulating water volume under the rated load. From the figure, it can be clearly seen that the efficiency of large flow rate and small temperature difference design method is larger than the large temperature difference and small flow design method.

![Figure 4](image-url)

Figure 4. Influence of Water Temperature on the Efficiency of the Boiler under Rated Load

The change in the heat output of the hot water boiler is characterized by the change of the temperature
difference and flow rate of the boiler inlet and outlet water. In the design document, what given is the thermal efficiency under the rated load of the boiler and few boiler design documents can give the efficiency under non-rated load. Generally speaking, under low load, the heat output of the boiler is reduced, which determines that the heat input of the boiler is reduced, accordingly, the furnace heat load is reduced, the heat exchange effect is deteriorated, and the boiler operation efficiency is lowered. When the boiler operating load is too high, the furnace heat load is higher than the designed value, and it is limited by the arrangement and area of the heating surface, more heat is discharged out of the furnace with the flue gas without exchanging heat with the heating surface, resulting in an increase in boiler exhaust loss, and the boiler efficiency is reduced. In the design process, since the heat loss of the boiler is the selected empirical data, while in actual operation, the value increases with the decrease of the load rate, so the corresponding value calculated under the low load according to the design is relatively high. However, it can be seen from Figure 5 that without considering the heat loss, when the boiler load rate reduces, the boiler efficiency increases.

4. Conclusion
Through the analysis of several main factors affecting boiler operating efficiency, the following conclusions are obtained:
(1) When the boiler is operated in a non-involved state, the boiler design efficiency will change greatly, and it can be corrected by multiplication factor. The correction coefficient can be obtained by data fitting.
(2) The analysis of several main factors affecting boiler operating efficiency has indirectly obtained that under the premise of other conditions being unchanged, the better the calorific value of fire coal, the higher the boiler efficiency; the lower the feed water temperature, the higher the thermal efficiency of the boiler; The higher the ambient temperature, the higher the efficiency of the boiler; the thermal efficiency of the boiler increases with the decrease of the load rate without considering the heat loss.
(3) From the perspective of operation, the boiler with high temperature difference and large flow rate has high efficiency.

REFERENCES
[1] Chen X, Chen T(1991). Boiler principle. Mechanical Industry Press,Xian.
[2] Wang X(2003). Characteristic and scope of AMSE PTC6 and PTC46. Power Engineering, 1:30-34
[3] Fan Y, Lin A(2006). Discussion on calculation method of heat input of CFB boiler. Northeast Electric Power Technology,27(2):7-8
[4] Mostaghimi P, Armstrong R T, Gerami A, et al(2017). Cleat-scale characterisation of coal: An overview[J]. Journal of Natural Gas Science and Engineering, 39:143-160.