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Research on the Method of Predicting Boiler Thermal Efficiency using Numerical Simulation

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ABSTRACT

The boiler thermal efficiency test requires strict operating conditions. Numerical simulation, which is considered as an economic and effective method to study the boiler combustion process, was adopted on a WNS2-1.25-Q gas-fired boiler. The combustion characteristics and boiler thermal efficiency were investigated. The simulation results are reliable, compared with thermodynamic calculation values. The results show that it is feasible to calculate boiler thermal efficiency by numerical simulation. This study can provide a new method for boiler efficiency calculation, which is beneficial to economics.

Keywords: boiler thermal efficiency, gas-fired boiler, combustion characteristic, numerical simulation

1. INTRODUCTION

Due to the backward technology, outdated equipment, the boiler thermal efficiency test conditions are difficult to reach a certain load condition of boiler energy efficiency test standard requirements.

CAE (computer Aided Engineering-computer Aided Engineering) simulation technology can be reasonably combining theory with practice [1], through the appearance, visual perception, combustion numerical simulation, using real boiler of proportion model or other models for reference, which can find boiler design, manufacture and the possible problems in use process [2-4].

The boiler thermal efficiency curve has been proposed in earlier years. Shi Li analyzed the characteristic curve change of the actual operating load and thermal efficiency of the quick-loading boiler, and discussed the reason of energy waste caused by the quick-loading boiler operating under low load and the improvement measures [5]. Shiro found that boiler efficiency is a function of load, excess air coefficient, flue gas temperature, baffle opening, etc. Wang proposed a two-stage hierarchical identification algorithm, which provides an effective calculation method for the identification of efficiency curves of various fuel boilers [6]. These studies provide a support and reference for this method.

According to the current literature, only a qualitative study on the calculation of boiler efficiency is carried out, and no quantitative analysis is made on the calculation of boiler efficiency. In this study, a method using numerical simulation for calculating boiler thermal efficiency is proposed. The effect of this method is proved by comparing the thermal calculation data of gas-fired boiler with the numerical simulation results. At the same time, the combustion characteristics of gas boilers under different operating conditions is investigated. This study provides a reference for boiler variable load operation and thermal efficiency calculation.

2. RESEARCH METHOD

Numerical simulation method was used to analyze the combustion and heat transfer characteristics of gas-fired boiler. Firstly, numerical simulation is carried out on the whole process of boiler combustion and heat exchange (burner, furnace, burnout chamber, two-pass flue, three-pass flue and economizer to exhaust outlet) under certain load. Then compare the data obtained by the numerical simulation with the thermal calculation data and the performance test data to confirm the calculation error of the simulation. Then the simulation parameters are modified to obtain a suitable numerical simulation model. Finally, the verified numerical model can be used to calculate the thermal efficiency of the gas boiler under various loads.

2.1 Boiler structure

The WNS2-1.25-Q gas-fired boiler studied in this study is a horizontal gas-fired boiler. The furnace is combustion chamber with corrugated pipe structure. Fig 1 shows the furnace structure. The high-temperature flue gas leaves the furnace, enters second return flue pipe and third return flue pipe in turn. The flue gas enters the economizer after convection heat transfer through the second and third return flue gas pipe, and then enters the atmosphere.

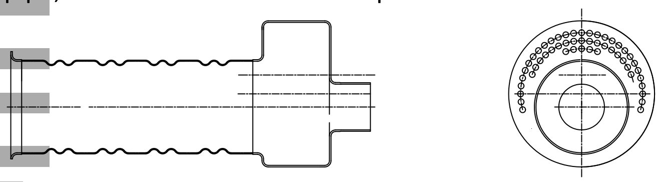


Fig 1 Furnace structure

2.2 Numerical model

The combustion process of natural gas in gas-fired boiler involves flow, heat transfer, combustion and other chemical processes.

The combustion process includes gas phase combustion and NO_x generation, and the heat transfer process includes radiation and convection heat transfer. In this study, SIMPLEC algorithm was used to solve the discrete algebraic equations. Realizable $k-\varepsilon$ model was adopted to simulate the turbulence process. Mixture Fraction PDF was performed to simulate the gas phase turbulent combustion process, and the P1 radiation model was adopted to calculate the radiation heat transfer process.

2.3 Boundary conditions

The inlet of primary air (PA), secondary air (SA), primary gas (PG) and secondary gas (SG) all adopt mass inlet conditions. The inlet mass and temperature are given according to thermodynamic calculation parameters. The inlet boundary conditions of furnace under different loads are shown in Table 1. All part boundary conditions are set as Table 2.

Table 1 Burner nozzle boundary conditions under different loads

Load/%	PA/kg s^{-1}	SA/kg s^{-1}	PG/kg s^{-1}	SG/kg s^{-1}
100.0	0.375	0.191	0.007	0.024
70.0	0.262	0.134	0.005	0.017
35.0	0.131	0.067	0.002	0.008

Table 2 The boundary conditions of each part under different loads

Load / %	Second return flue pipe/ kg s^{-1}	Third return flue pipe/ kg s^{-1}	Economizer / kg s^{-1}
100.0	0.011708	0.012980	0.033876
70.0	0.008195	0.009086	0.023713
35.0	0.004098	0.004543	0.011857

2.4 Numerical simulation reliability analysis

According to GB/T 10180-2017, For the gas-fired boiler, the thermal efficiency of the boiler can be calculated by using the inverse balance method to calculate the heat loss. The calculation formula is as follows.

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

η -- Thermal efficiency, %;
q_2 -- Smoke emission heat loss, %;
q_3 -- Gas incomplete combustion heat loss, %;
q_4 -- Heat loss from incomplete combustion of solids, %;
q_5 -- Heat dissipation loss, %;
q_6 -- Ash physical heat loss, %;
q_7 -- Heat loss from desulfurization of limestone, %.

Under the calculation system of the counterbalance method, q_7 is excluded because the natural gas boiler does not use desulfurization in the furnace. After the complete combustion of natural gas, there is no solid residue, and there is no incomplete combustion of solid or liquid fuel. In other words, the physical heat loss of ash residue q_6 and mechanical heat loss q_4 can be ignored. For boilers with reasonable structural design and normal operation, the heat loss of chemical incomplete combustion is almost zero. Boiler capacity, load and ambient temperature of boiler outer surface will have an impact on heat dissipation loss q_5. This numerical simulation mainly considers the reliability of combustion heat transfer simulation, so heat dissipation loss is also temporarily ignored. To sum up, the most important component of heat loss of natural gas boiler is heat loss q_2 of exhaust smoke.

Therefore, the smoke exhaust heat loss is mainly considered in the comparison between the numerical simulation and the thermodynamic calculation data.

Under the same load, namely, the data deviation of smoke exhaust temperature is analyzed. When the boiler thermal efficiency is calculated according to the reverse balance in the Thermal Performance Test Rules for industrial Boilers, it is qualified if the difference between the two thermal efficiency values is not more than ±1%. Relevant literature and engineering application all show that when the dew point temperature is higher than the above temperature, the variation of smoke exhaust temperature from 12~15 °C can affect the boiler efficiency by about 1% [7].

2.5 Simulation results and analysis

2.5.1 Reliability verification of numerical simulation

In order to verify the reliability of the numerical simulation, the numerical simulation results under 100% BMCR load were compared with the thermodynamic calculation values. Table 3 shows the comparison between numerical simulation and thermal calculation data.

Table 3 Comparison of numerical simulation and thermal calculation data

item	furnace	Third return flue pipe	economizer
Design inlet flue gas temperature/ °C	/	359.0	239.8
Simulate inlet flue gas temperature/ °C	/	387.2	229.8
Design outlet flue gas temperature/ °C	990.1	239.8	69.3
Simulate outlet flue gas temperature/ °C	981.9	229.8	76.7

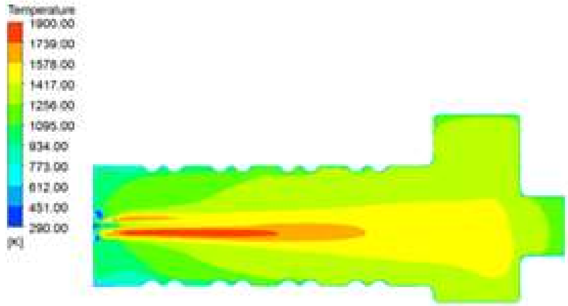
It can be seen from Table 3 that the simulated smoke temperature at the outlet of the burnout chamber is 8.1 °C lower than the thermal calculation data. The simulated smoke temperature at the three-return exit is 10.1 °C lower than the thermal calculation and the simulated smoke temperature at the outlet of the energy saving device is 7.4 °C higher than the thermal calculation data.

According to section 2.4, it can be seen that the numerical simulation results are within the acceptable range of efficiency calculation, so it can be considered that the selection of the numerical simulation model and the calculation results are reliable.

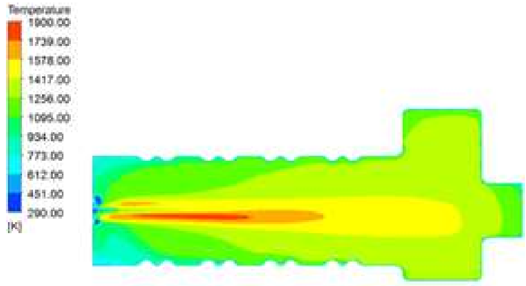
2.5.2 Combustion characteristics under different loads

The results of boiler combustion under different loads can be seen from the temperature distribution diagram, as shown in Fig 2. The combustion flame is more balanced. At 100% load, the flue gas temperature is still high in the combustion chamber, and the flue gas filling degree of high temperature is better.

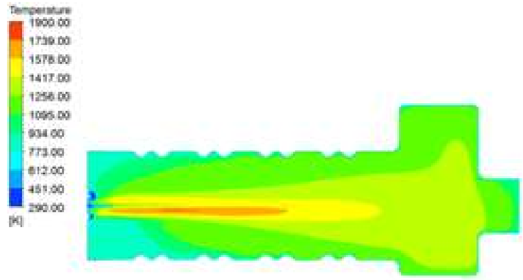
As the load decreases, the high temperature area of the burnout chamber gradually decreases, indicating that the natural gas can be completely burned out. Generally speaking, the boiler chamber and burnout chamber size can match the burner flame length and flame diameter.



a.100% BMCR



b.70% BMCR



c.35% BMCR

Fig 2 Temperature distribution in furnace under different load

Fig 3 shows the temperature distribution along furnace section under different load. The flue gas temperature along the furnace section rises with increasing the boiler load. That's because, with the increase of fuel furnace heat quantity, water wall absorption heat gain mismatch, leading to the rise of flue gas temperature.

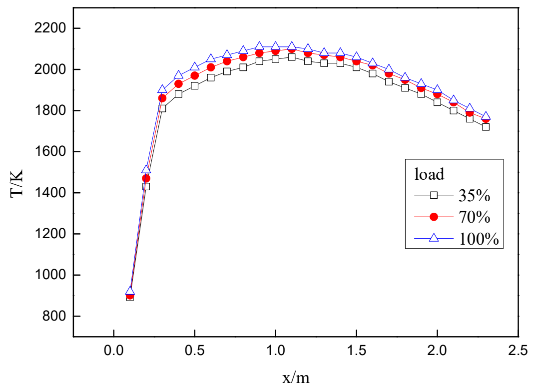


Fig 3 Temperature distribution along the cross section of furnace under different loads

Fig 4 shows the change of flue gas composition at the outlet of the burnout chamber under different loads. It can be seen that with the increase of furnace load, the volume concentration of CH_4 at the outlet of the burnout chamber is near zero, indicating that the degree of natural gas burnout is good under each load.

In addition, when the boiler load increases from 35% to 100%, the volume fraction of CO increased slightly, while the volume fraction of CO_2 slightly decreases. This is caused by the air staging technology. With the increase of furnace load, lean oxygen zone in the furnace also increases.

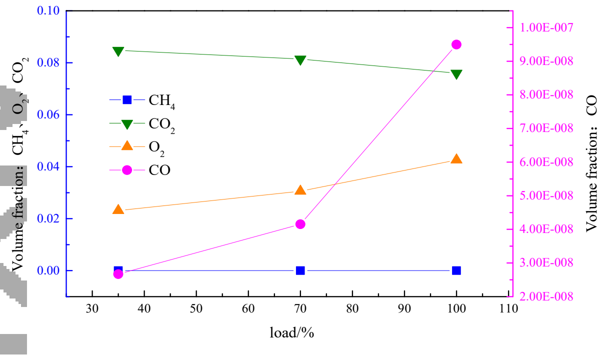


Fig 4 Flue gas composition at the outlet of the combustion chamber under different loads

2.6 Conclusions

Numerical simulation method was used to calculate the combustion process of WNS2-1.25-Q gas-fired boiler. The following conclusions are obtained.

In this study, a method using numerical simulation for calculating boiler thermal efficiency is proposed. The validity of the method of calculating boiler thermal efficiency by using numerical simulation is verified and analyzed by comparing the thermal calculation data of gas boiler with the numerical simulation results. Using numerical simulation to calculate boiler thermal efficiency, the boiler thermal efficiency can be controlled at ±1%.

The temperature distribution, velocity distribution, oxygen concentration distribution and carbon dioxide concentration distribution of the furnace were obtained under 35% load, 70% load and 100% load of the designed fuel.

With the decrease of furnace load, the high temperature area of burnout chamber gradually decreases, while the volume fraction of outlet CO decreases, indicating that natural gas can be completely burned out at low load. Generally speaking, the boiler chamber and burnout chamber size can match the burner flame length and flame diameter.

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