Analysis of Flue Gas Emission from Gas-fired Wall-mounted Boilers

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Abstract: With the continuous promotion of the coal-to-gas policy in major towns in Beijing and its counties, Hebei, Shandong, and some provinces in Northwestern China, the proportion of household heating in the winter heating market has increased year by year. As one of the main heating equipment, the sales of wall-mounted gas boilers are also increasing year by year. Due to the concentration of installations in cities, the NO_x and CO emissions generated by the operation of a huge number of gas-fired wall-mounted boilers gradually appear to have an impact on the environment. This article will measure NO_x and CO in the emissions of common gas wall-mounted boilers on the market (including conventional atmospheric gas wall-mounted boilers, low-NO_x wall-mounted boilers, secondary condensation low-NO_x wall-mounted boilers and fully premixed gas wall-mounted boilers). Through the quantitative analysis and comparison of the data, a reference is given to the selection of the gas wall-mounted boiler.
***Keywords*:** coal-to-gas, gas-fired wall-mounted boiler, NO_x, CO

1. Research background

With the emergence of extreme weather such as smog across the country, environmental pollution has gradually aroused people's attention, prompting various research institutions to actively explore the main causes of smog. Studies have found that the main man-made causes of smog are industrial production, emissions from coal-fired flue gas and automobile exhaust, and emissions from heating boilers in civil buildings in winter. Especially the flue gas emitted by small coal-burning boilers for heating in winter has a greater impact [1]. Therefore, the winter haze in the north has always been more serious than that in the south. At the same time, it is also found that the concentration of NO_x oxides (NO_x) in the air is directly related to the formation of haze [2]. In order to avoid the formation of smog, the country promulgated a coal-to-gas policy in 2016, starting from Beijing and Hebei Province and gradually promoting it. At the same time, the extensive laying of urban infrastructure such as natural gas pipelines provides basic conditions for the decentralized use of gas combustion equipment [3]. Household gas wall-mounted boiler heat source heating has gradually become the mainstream choice for independent heating because of its flexible start and stop, clean and hygienic, easy-to-adjust power, and simple metering [4]. Figure 1 shows the sales of gas wall-mounted boilers in the past 10 years [5]. From 2011 to 2020, the annual output of wall-mounted gas-fired boilers in my country has continued to increase, and its market share has increased year by year. Especially after the country promulgated the coal-to-gas policy in 2016, the gas-fired wall-mounted boiler reached a sales peak of 5.5 million units in 2017. Although the adjustment of relevant local policies in 2018 and the temporary shortage of gas supply in the winter of 2017 caused the overall sales of gas wall-mounted boilers to decline in 2018, their sales increased in 2019.

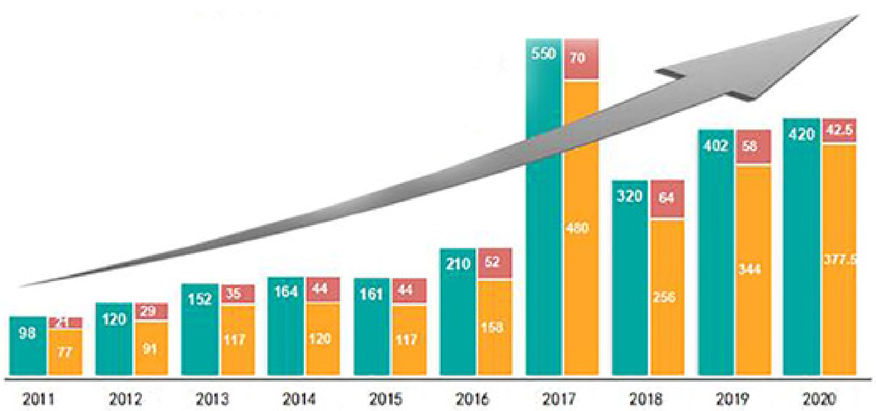


Figure 1. 10-year market sales (10,000 units) statistics of gas-fired heating water heaters[5]

It can be seen from Figure 1 that the market sales of wall-mounted boilers have become increasingly mature in the household heating market in the past 10 years. Although compared with small coal-fired boilers, gas-fired boilers have obvious advantages in energy saving and environmental protection, but with the increase in the use of gas-fired wall-mounted boilers year by year, and the use of gas-fired wall-mounted boilers is concentrated in cities, the combustion of "clean" gas-fired wall-mounted boilers Emissions pollution has gradually aroused people's attention.

2. Pollutant emission in flue gas of gas-fired wall-mounted boiler

The wall-mounted gas boiler is mainly fueled by clean natural gas. There are two types of flue gas pollutants: NO_x oxides (NO_x) in the flue gas after combustion, and CO caused by incomplete combustion.

2.1 NO_x in flue gas of gas wall-hung boiler

NO_x is one of the main sources of air pollution. Generally speaking, NO_x has many different forms, including N_2O, NO, NO_2, N_2O_3, N_2O_4 and N_2O_5. Among them, NO and NO_2 are the main air pollutants. There are three sources of NO_x. 1) Thermal type (temperature type) NO_x means that NO_x in the air is oxidized at high temperature to generate NO_x. 2) Rapid temperature NO_x refers to the reaction of oxygen and NO_x in the air with hydrocarbon ion groups such as CH in the fuel to generate NO_x when burning hydrocarbon fuels. 3) Fuel-type NO_x refers to the thermal decomposition of NO_x-containing compounds in the fuel during the combustion process, and then further oxidation to generate NO_x. For gas-fired wall-mounted boilers that burn natural gas, both thermal and rapid temperature NO_x may exist.

The general chemical reaction equation of rapid temperature type NO_x is:

$$N_2 + O_2 = 2NO \ \Delta H{=}180.5 kJ/mol \tag{1}$$

This chemical reaction is an endothermic reaction. The high temperature state is conducive to the formation of NO, and NO is easily oxidized by oxygen O_2 to form NO_2.

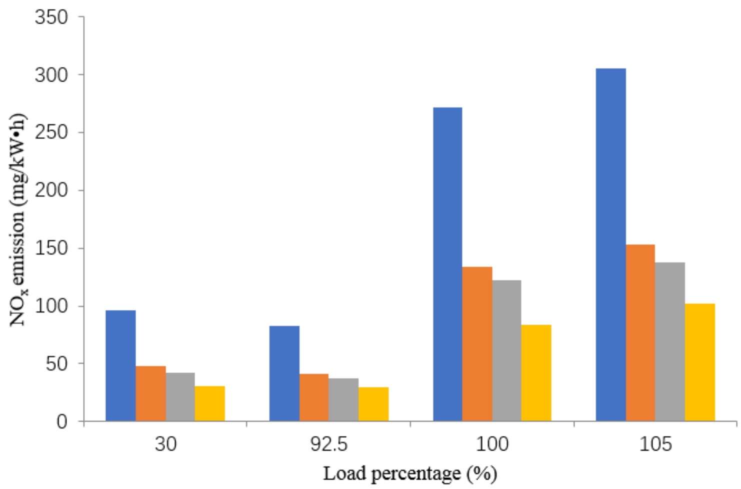
$$2NO + O_2 = 2NO_2 \ \Delta H{=}{-114.1} kJ/mol \tag{2}$$

In addition, the carbon monoxide CO produced due to incomplete fuel combustion can also affect the composition of NO_x:

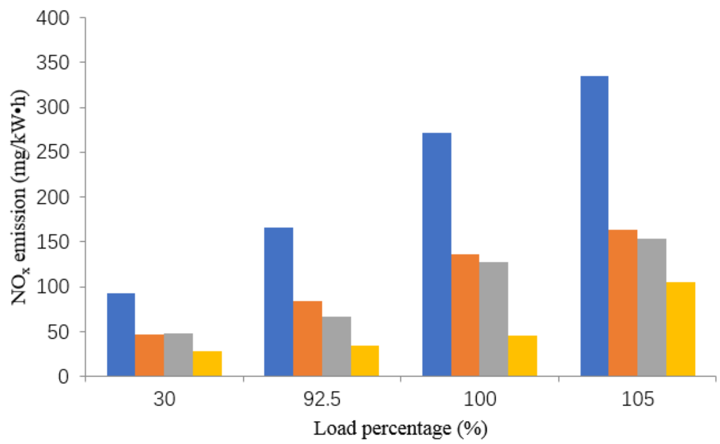
$$NO_2 + CO = NO + CO_2 \tag{3}$$

In summary, in the structural design of the gas-fired wall-mounted boiler, methods of reducing the flame temperature and avoiding local high temperatures are mainly adopted to reduce the generation of thermal NO_x oxides NO_x in the flue gas; fans are used to shorten the residence time in the high temperature zone; The premixed gas method balances the oxygen content to reduce the generation of thermal and rapid temperature NO_x.

Figure 2 shows the comparison of NO_x emissions of four different types of boilers burning G20[6] gas under different working modes and different loads. In this study, two different boilers of the same type were measured for data recording in each working condition, and the average value was taken to be compared (the same below).



a. Heating mode (ordinary boiler, low-NO_x boiler, secondary low-NO_x condensing boiler, fully premixed condensing boiler)



b. Domestic hot water mode (ordinary boiler, low-NO_x boiler, secondary low-NO_x condensing boiler, fully premixed condensing boiler)

Figure 2. Comparison of NO_x emissions of four gas boilers burning G20 gas

(1) The influence of boiler working mode.

The domestic hot water mode of the gas boiler is that the heating water passes through the plate heat exchanger to heat the domestic hot water. It can be seen from Figure 2 that when the outlet temperature of domestic hot water is set at 50°C and the heating is also set at 50°C, the NO_x emissions in the heating mode are lower than the NO_x emissions in the domestic hot water mode. This is determined by the operating mode of the wall-mounted boiler. The output of domestic hot water is to use hot water to heat domestic cold water through a plate heat exchanger. Therefore, in the domestic hot water mode, the outlet water temperature of the heat exchanger is greater than that of the domestic hot water. It can also be understood that when the gas boiler is in operation, the temperature of the outlet water in the summer test is higher than the heating and water supply requirements in the winter, and the flue gas temperature of the gas boiler is relatively higher. In addition, in different working modes, the higher the boiler load, the higher the NO_x emissions. This is because the higher the load, the more gas will be burned in the combustion chamber of the same size. Therefore, the higher the flue gas temperature, the more thermal NO_x will be produced. At the same time, the flue gas temperature has a very obvious effect on the generation of thermal NO_x. The higher the flue gas temperature, the higher the proportion of NO_x in the flue gas.

(2) Emission comparison of different types of wall-mounted boilers.

As shown in Figure 2, no matter in heating or domestic hot water mode, the NO_x emissions of ordinary boilers are the highest, followed by low-NO_x gas-fired boilers. This is caused by its structural characteristics. The low-NO_x gas boiler only has a return pipe on the burner, and the flame temperature of the burner is lowered. After the natural gas is burned, it exchanges heat with the main heat exchanger and is directly discharged to the outdoors through the flue pipe. The final flue gas temperature is second only to that of the ordinary boiler. On the basis of the low-NO_x gas boiler, the secondary condensing gas wall-mounted boiler has a secondary condensing heat exchanger, which further reduces the temperature of the flue gas, so that the thermal NO_x content in the flue gas is further reduced. The fully premixed condensing gas boiler will fully premix natural gas and air and then spray it into the combustion chamber for combustion. The combustion surface temperature of the flame is inherently very low. In addition, the heat exchanger structure of the fully premixed boiler is that the main heat exchanger and the secondary condensing heat exchanger are together to form the outer cavity of the combustion chamber. The flue gas must pass through the condensing heat exchanger to enter the flue pipe and be discharged into the atmosphere, which further reduces the flue gas temperature and further reduces the amount of thermal NO_x produced. In addition, the fuel-type NO_x after the G20 combustion is relatively small. As a thermal-type NO_x-dominant gas boiler, the excess air coefficient increases, and the amount of air that is not involved in combustion increases. This part of the air will take away a lot of heat and reduce the flame. Temperature, the thermal NO_x generation capacity is weakened, so that the measured concentration of NO_x decreases.

2.2 CO content in flue gas under extreme heat input state

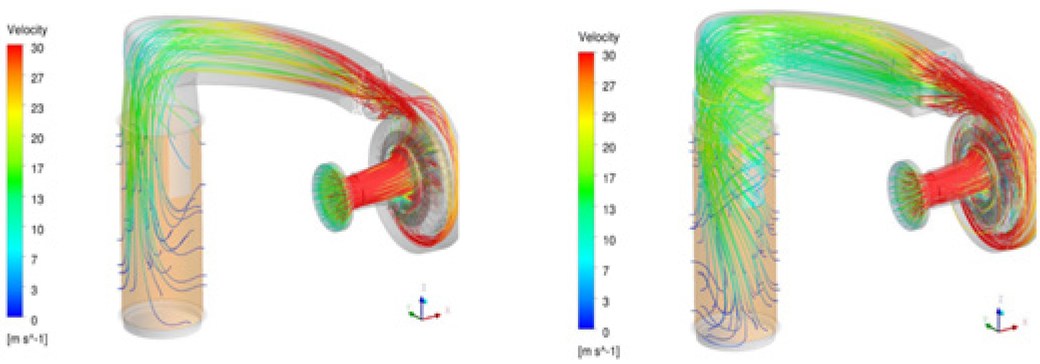
Table 1 shows the CO emission test values of four gas-fired wall-mounted boilers burning G20, G21 and G23 [6] gas under different loads. For all tests, the longest smoke pipe test is selected for testing, because it is easy to test the CO value in the case of incomplete combustion when the resistance of the smoke pipe is the largest.

Table 1. CO emission values of boilers under different loads and various gas conditions

Gas boiler type	Test gas type	Load	Maximum flue pipe length (m)	CO test value (ppm)
	G20	105%		162
Ordinary boiler	G21	105%	3	195
	G23	95%×minimum load		130
	G20	105%		112
Low NO_x boiler	G21	105%	3	145
	G23	95%×minimum load		89
	G20	105%		82
Secondary condensing boiler	G21	105%	3	129
	G23	95%×minimum load		57
	G20	105%		32
Fully premixed boiler	G21	105%	5	55
	G23	95%×minimum load		22

The special working condition is the working condition of 105% overload and 95% minimum load. In the installation of the boiler's longest flue pipe, G20, G21 and G23 are used to test the amount of CO in the boiler flue gas. Through comparison and analysis, it can be clearly found that under extreme conditions, when using G21 and 105% overloaded rated load, the CO content of gas-fired boilers in the flue gas is the highest compared with other types of gas used respectively; when using G23 gas, The CO content of gas boilers is the lowest in the flue gas of their respective boilers. Among the four types of boilers, the CO emissions of the fully premixed gas-condensing hybrid boilers are the lowest, and the ordinary boilers are the highest. The greater the amount of CO, the less adequate the combustion of gas.

The CO concentration ratio of flue gas produced by different gas in the same boiler: G21>G20>G23. The CO content ratio of flue gas produced by the same gas in different boilers: ordinary boiler> low NO_x boiler> secondary condensing boiler> fully premixed boiler. It can be seen from the above results that the CO value of the flue gas emissions of the secondary condensation and the fully premixed condensing boiler is very low, but the CO emission value of the fully premixed condensing boiler is the lowest. The minimum CO content in the flue gas of a fully premixed boiler is determined by the fully premixed combustion mode. In order to achieve ideal combustion, the CO emissions of a fully premixed boiler under different excess air coefficient premix ratios were tested. The CO content in the flue gas of this fully premixed gas boiler fluctuates greatly with the premixed excess air coefficient. When the excess air coefficient is 1, CO is produced in a large amount. From the numerical simulation (Figure 3a), the air and gas are not uniformly mixed at this time, and the velocity vector in front of the burner exit is not uniform enough, resulting in insufficient combustion in some areas, and unburned CO in the burning area. When the excess air coefficient is 1.2-1.5, CO is basically 0. At this time, the CO_2 content in the flue gas is in the range of 8% to 10%. Therefore, the CO_2 emission can be judged by the CO_2 concentration. From the numerical simulation, when the excess air coefficient is 1.3 (Figure 3b), the velocity vector in front of the burner exit is very uniform, and the gas injected into the combustion chamber can be burned uniformly, so the CO is zero.



a. The excess air coefficient is 1 **b. The excess air coefficient is 1.3**

Figure 3. Fully premixed air gas velocity vector diagram

But when the excess air coefficient is greater than 1.2-1.5, the heat generated by combustion is diluted and shared by a large amount of air, and the average temperature of the flue gas is too low, which will also cause incomplete combustion and CO begin to rise again.

3. Comparison of the temperature field of the heat exchanger of the secondary condensing and the full premixed condensing boiler

The NO_x emissions of secondary condensation and full premixed condensing boilers are relatively low, but in comparison, the NO_x emission of full premixed condensing boilers is lower than that of secondary condensing boilers. This is mainly because the structure of the condensing heat exchanger and the secondary condensing heat exchanger are different, which directly causes the temperature fields of the two products to be different. Using simulation analysis to compare the temperature field of the heat exchanger can explain the reason. Regarding the analysis of the temperature field of the secondary condensing heat exchanger, Professor Zhou Weiguo of Tongji University used FLUENT analysis software to do related research and analysis [7], see Figure 4. The fully premixed condensing boiler takes the Vitodens 100 model boiler produced by Viessmann as an example for finite element analysis (FEA) analysis.

The secondary condensing heat exchanger is after the main heat exchanger, and its temperature field cloud diagram is shown in Figure 4. It can be seen that the temperature distribution is not uniform. Especially in the red area, the high-temperature flue gas enters the secondary condensation heat exchanger area after a period of time, and then the flue gas temperature gradually decreases as the heat exchange progresses. The temperature field of the flue gas is not uniform.

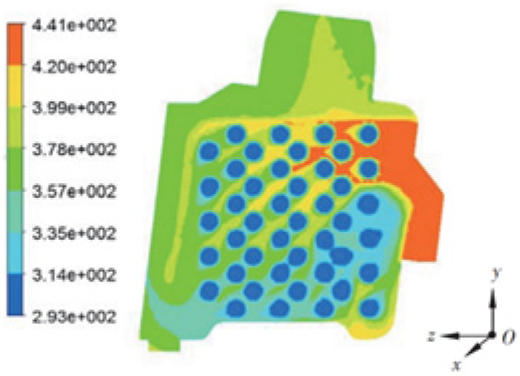


Figure 4. Temperature cloud diagram of secondary condensing heat exchanger [7]

The fully premixed condensing boiler uses the heat exchanger as the combustion chamber and the center of the heat exchanger as the axis, and conducts radiation and convection heat transfer to the surface of the heat exchanger in the combustion chamber. The gas and air are mixed and sprayed into the combustion chamber, and the temperature of the ignited flue gas passes through a fully premixed condensation heat exchanger, and its temperature drops rapidly. The temperature field of the heat exchanger that is the combustion chamber is shown in Figure 5. With the help of FEA software analysis, the cold flame temperature of this fully premixed burner is greater than 1500°C, but the flue gas temperature after passing through the condensing heat exchanger It quickly drops below 60°C, and the temperature field changes uniformly. Therefore, the layout of the flue gas temperature field of the fully premixed condensing boiler effectively reduces the generation of thermal NO_x.

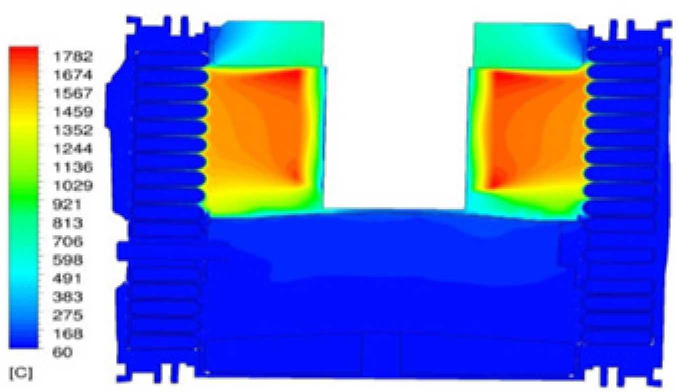


Figure 5. The combustion flame temperature and heat exchanger temperature cloud diagram of the fully premixed condensing furnace

4. Conclusion

Through the study of the NO_x and CO emissions in the flue gas of four gas-fired wall-mounted boilers burning G20, G21 and G23 gas under different loads and the heat exchange efficiency of the boiler, the results show that after the ordinary gas-fired wall-mounted boiler burns G20, the smoke The NO_x in the gas is the highest among the four boilers; the CO value in the flue gas of the fully premixed boiler is the lowest among the four boilers.

(1) The NO_x emissions in the flue gas produced by four gas-fired wall-mounted boilers burning G20 are compared. The NO_x emissions sequence in heating and domestic hot water working modes is: full premixed boiler <secondary condensing boiler <low NO_x boiler <ordinary boiler. And it is found that the NO_x emission of the fully premixed condensing boiler at part load is the lowest, while the NO_x emission of the ordinary boiler is the highest. Low-NO_x, secondary condensing and fully premixed boilers can meet the national mandatory product standard GB25034-2010 NO_x emission level 5 requirements, but only fully premixed condensing gas boilers can meet Beijing's NO_x emission requirement of 30 mg/m3. In the heating season, gas wall-mounted boilers are operated under partial load most of the time. Therefore, the large-scale application of the fully premixed condensing boiler in the household heating system will greatly reduce the NO_x emission in the winter heating season in northern my country.

(2) The CO emissions in the flue gas of four gas-fired wall-mounted boilers are studied. The proportion of CO in the flue gas will change with the combustion status and the type of natural gas. Moreover, it was found that as the ratio of NO_x in the flue gas increased, the ratio of CO in the flue gas decreased instead. But in general, the CO emissions of the four boilers are not high, not exceeding 1000 ppm, which will not affect the users and the environment.

Statistics have been carried out since 2017 when the coal was converted to gas. As of 2020, the calculation is based on an average of less than 4 million gas-fired wall-mounted boilers per year. If all premixed condensing boilers are used, the NO_x emissions of gas wall-mounted boilers instead of central heating will be reduced by more than 60% every year. The conversion of coal to gas and household heating will contribute more to environmental protection.

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