ISSN: 2414-1895 DOI: 10.6919/ICJE.202401_10(1).0009

Development of a MILD Burner based on External Flue-gas Recirculation

Xiaomin Li, Kunfeng Sun

School of Energy & Environment, Zhongyuan University of Technology, Zhengzhou 450007, China

Abstract

This paper presented a MILD burner based on the external exhaust gas recirculation technique aiming at ultra-low NOx emissions. A furnace with central reverse flame was used to solve the serious incomplete combustion when the external flue-gas recirculation rate (FGR) is higher than 20%. Comprehensive measurement was conducted on the burner with thermal output of 700kW. There exists no CO in the exhaust gas and the average deviation between the measurement value and the theoretical value of CO_2 and O_2 concentration ranges from 0.01% to 0.03%. When FGR is equal to zero, NOx emissions range from 71 to 134mg/m^3, which is 30~40% lower than the traditional flame. When FGR exceeds 30%, NOx emissions are below 40mg/m^3. When FGR increases from 40% to 50%, NOx emissions range from 8 to 28 mg/m^3.

Keywords

Flue-gas; Moderate & Intense Low Oxygen Dilution Combustion; Central Reverse Flame; Nitrogen Oxides.

1. Introduction

Nitrogen oxides (NOx) are highly reactive air pollutants and cause photochemical smog, acid rain, environmental degradation[1]. It is indispensable for combustion systems to find a reliable and cheap solution to reduce NOx emissions without compromising the combustion efficiency[2]. In natural gas-fired boiler, thermal NOx is largely predominant and account for more than 90%. Thermal NOx formation is correlated with the flame temperature and the availability of oxygen. As a matter of fact, flame temperature should be lower than a threshold temperature of about 1100 °C to keep NOx emissions at a minimum.

According to the mechanisms of thermal NOx formation, external exhaust gas recirculation technique was extensively employed to suppress thermal NOx formation. Here partial exhaust gas is recirculated to mix with the comburent air and form a low oxygen dilution oxidant. Its applications show that the peak flame temperature decreases by about 40K and NOx emissions can be reduced by 20~50% when the external exhaust gas recirculation rate increases by 5%[3]. However, when the external exhaust gas recirculation rate further increases and exceeds 20%, ignitability will severely deteriorate[4]. Moreover, there also exists a serious incomplete combustion loss. Therefore, it is necessary to take auxiliary measures to stabilize the flame, e.g. appending swirler or blunt body[5, 6]. The measures above can accordingly make the burner structure more complex by all means and its pressure drop also increases dramatically. As a result, manufacturing and operation cost of the burner can increase sharply and account for 20~40% of the whole boiler. Therefore, to further reduce NOx emissions by means of the external exhaust gas recirculation, it is necessary to combine it with other low NOx technology to design the combustion systems. In this study, we combine the external exhaust gas recirculation technique with moderate and intense low oxygen dilution (MILD) combustion technology to achieve the goal of ultra-low NOx emissions.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202401_10(1).0009

To achieve ultra-low NOx emissions in nature gas-fired boiler or generator of absorption refrigerator, we develop a novel MILD combustor based on the external exhaust gas recirculation technique. Moreover, a furnace with central reverse flame was adopted to solve the problems of combustion instability and incomplete combustion, due to the higher external exhaust gas recirculation rate adopted in present study. The furnace can not only prompt to the mixing between the in-furnace high temperature exhaust gas and the input diluted oxidant by countercurrent manner, but also supply hot diluted oxidant required for MILD combustion. In order to quantitatively know effect of the external exhaust gas recirculation rate on NOx emissions and combustion performance of the furnace, an experimental investigation was conducted on a pilot-scale nature gas-fired boiler, with thermal power of 700kW and saturated steam temperature of 425ºC.

2. Experimental

In this work, a novel MILD burner was proposed and installed in a cylindrical combustion chamber as shown in Fig.1.

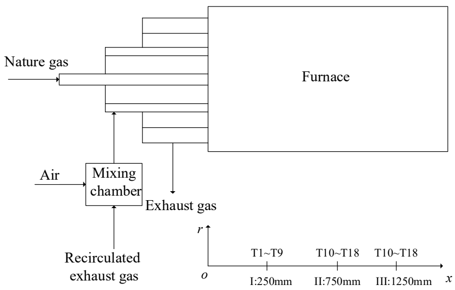

Fig.1. Schematic of the MILD combustion apparatus.

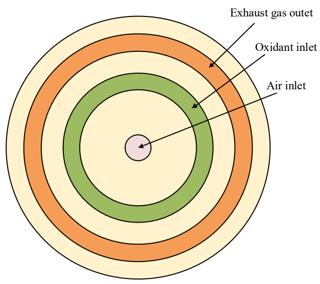

Fig.2. Schematic of the MILD burner configuration.

The furnace is made of Q235-A materials with a circular across-section, 650 mm dia., and net length, 1600 mm, and wall thickness, 12mm. The combustion chamber operates at thermal power of 700 kW. The burner consists of a central fuel nozzle, an annular air inlet and an annual outlet, as shown in Fig.2. Natural gas was fed to the furnace through the central nozzle. Thermal power can be regulated by the manual regulating valve and the mass flowmeter controller. Comburent air and recirculated exhaust gas are fed into the mixing chamber to form the diluted oxidant. Exhaust gas enters the reversal chamber through the annular outlet, which also located in the front wall. B-type thermocouple is used to measure the in-furnace temperature. Wire diameter of the thermocouple is 0.5mm and its measuring error is in range of ±1ºC. There are 27 thermocouples in total arranged on section I, section II and section III respectively (see Fig.1). For each section, there are six thermocouples evenly arranged along the radial direction. A K-type thermocouple is used to measure the temperature of the exhaust gas. Wire diameter of the thermocouple is 1.5mm and its measuring error is in range of ± 0.75% of the measured value. Composition of the exhaust gas is measured through a gas analyzer, TESTO 350. The sensors were calibrated before each measurement to avoid signal intensity degeneration. To quantitatively know the effect of the external exhaust gas recirculation ratio on NOx emissions and combustion efficiency, an experiment was executed involved 6 working cases, i.e. the external exhaust gas recirculation rate equal to 0%, 10%, 20%, 30%, 40%, 50% respectively.

3. Results and Discussion

3.1 NOx Formation of the MILD Burner and the Traditional Burner

NOx in the exhaust gas for the MILD burner was plotted as a function of the excess air coefficient in Fig. 3:

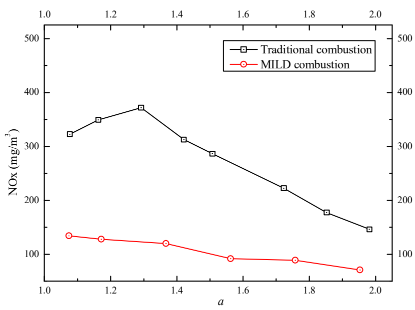

Fig.3. NOx content in the exhaust gas between the traditional burner and the MILD burner.

In Fig.3, symbol α denotes the excess air coefficient and the surroundings air is used as the oxidant. To quantitatively know the capacity of the MILD burner to suppress NOx formation, Fig. 3 also shows NOx emissions in a traditional burner, an annular tube burner with the same thermal power. It can be seen from Fig.3 that NOx emissions in traditional combustion mode range from 150 to 371mg/m^3, where the excess air coefficient in range of 1.05~1.98. Nevertheless, NOx emissions in mild combustion are in range of 71~134mg/m^3, which is 30~40% lower than that in traditional combustion. This is attributed to that the spacings between the fuel nozzle and the oxidant nozzle is distant, 80mm, which makes enough in-furnace high temperature flue gas be entrained before the fuel jet encounter with the oxidant jet. This configuration facilitates to form both the hot diluted fuel stream and the hot diluted oxidant stream.

In nature gas-fired boiler, Eq. (1) is used to calculate NOx content in the exhaust gas:

$$\frac{dC_{NO}}{dt}=3\times10^{14}\exp\left(-\frac{54200}{RT}\right)C_{N_2}C_{O_2}{}^{1/2} \tag{1}$$

Where CNO, CN2, CO2 denote the mole concentration of NOx, N2, O2, t denotes time, R denotes the universal gas-law constant, T denotes temperature. According to Eq. (1), we can know that, the formed combustible gas mixture where the hot diluted fuel stream encounter with the hot diluted oxidant stream is in a state of high-temperature and low oxygen concentration for MILD combustion. This results in that the chemical reaction speed and the local heat release rate are low comparing to the traditional combustion, which makes the NOx formation in MILD combustion much lower than that in traditional combustion. Moreover, it can also be seen from Fig. 3 that NOx formation in both combustion manners first increases and then decreases with the increase of the excess air coefficient. This shows that both temperature and oxygen concentration have an impact on NOx formation, but their action strength are distinct. When the burner operates in a state of lower excess air coefficient, i.e. a state closer to stoichiometric ratio, a higher flame temperature appears inside the furnace. NOx formation is hence mainly affected by oxygen concentration and increases with the increasing excess air coefficient. On the contrary, when the burner operates in a state of higher excess air coefficient,

ISSN: 2414-1895
DOI: 10.6919/ICJE.202401_10(1).0009

diluted effect plays a more crucial role due to entraining substantial in-furnace flue gas. The diluted effect continuously strengthens with the increase of the excess air coefficient, which make the flame temperature enough low and suppress thermal NOx formation. In addition, it can also be seen from Fig. 3 that, although NOx formation for the MILD burner is much lower than that in the traditional burner, its quantity still amounts to 71~134mg/m^3. This shows that, although MILD combustion is capable of suppressing NOx formation, it is still unable to meet with the legislation requirement implemented in China. Therefore, it is necessary to combine MILD combustion technology with other low NOx combustion technology to reduce NOx emissions.

3.2 Effect of the External Exhaust Gas Recirculation Rate on NOx Formation

The external exhaust gas recirculation technique is extensively utilized in area of gas-fired boilers owing to its briefness and low NOx emissions. The external exhaust gas recirculation involves the partial exhaust gas is recirculated to a mixing chamber by a fan and mix with air to form a diluted oxidant with oxygen concentration less than 21%. Oxygen concentration of the diluted oxidant is plotted as a function of the external flue-gas recirculation rate in Fig. 4. It can be known that oxygen concentration of the oxidant decreases with the increase of the external exhaust gas recirculation rate. Lower oxygen concentration essentially facilitates to suppress NOx formation.

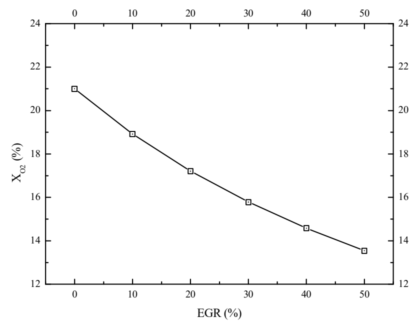

Fig. 4. Oxygen concentration of dilute oxidant vs. the external exhaust gas recirculation rate.

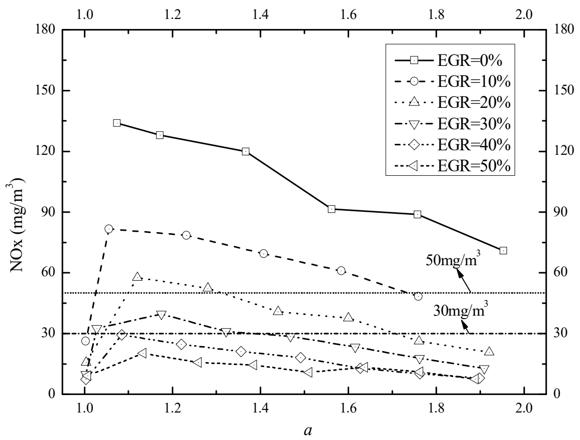

Fig.5. NOx emissions of MILD combustion when the external exhaust gas recirculation rate equal to 0%, 10%, 20%, 30%,40%, 50% respectively.

However, when the external exhaust gas recirculation rate continues to increase and higher than 20~30%, which can interfere with the combustion progress, especially the combustion instability and the incomplete combustion. In view of the problems resulted from the higher exhaust gas recirculation rate, the present work adopts a furnace with central reverse flame. This arrangement makes the high temperature exhaust gas, about 1100°C, contact with the diluted oxidant in countercurrent manner, which is helpful to efficiently mix their two and improve ignitability.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202401_10(1).0009

Fig. 5 presents the effect of the excess air coefficient on NOx emissions when FGR is equal to 0%, 10%, 20%, 30%, 40%, 50% respectively. It can be known from Fig.5 that NOx content in the exhaust gas first increases and then decreases with the increase of the excess air coefficient. This further verify the conclusion obtained in section 2.1 of this paper. NOx content in exhaust gas is 71~135 mg/m^3, 26~82 mg/m^3, 16~58 mg/m^3, 10~40 mg/m3, 8~28 mg/m^3, 9~21 mg/m^3 respectively when FGR is equal to 0%, 10%, 20%, 30%, 40%, 50% respectively. Combined with the present air pollutants emissions legislation, NOx emissions can meet with the emissions limit requirement of 50mg/m^3 when FGR is higher than 30% and can meet with the emissions limit requirement of 30mg/m^3 when FGR is higher than 40%. Moreover, when the furnace operates in a working case of approaching to the stoichiometric ratio, NOx emissions significantly reduce with the increase of the exhaust gas recirculation rate, up to a minimum of 8 mg/m3. Besides that, this is also consistent with the current viewpoints, namely, to suppress NOx formation by operating gas-fired boiler in a working case near to the stoichiometric ratio.

3.3 Combustion Characteristics of the MILD Burner

To avoid excessive dilution of the oxidant, the external exhaust gas recirculation rate is usually set to no more than 30% in design of a nature gas-fired boiler. On the premise of which, NOx emissions can accordingly reduce, up to a maximum spectrum of 70%, comparing to the traditional combustion. The combustor geometry then become complex due to a swirler addition and the manufacturing cost increase sharply, up to 40%~50% of the whole boiler. Even though, the absolute NOx emissions in the exhaust gas still exceeds 50mg/m3 and is unable to meet with the limit emissions requirements. In this regard, it is more convenient to decrease NOx emissions by further increasing the external exhaust gas recirculation rate. Therefore, it is necessary to design the burner more stringent. Notes that thermal recirculation reactor strategy is a reliable and cheap solution to stabilize the flame, the key of which was to utilize materials with high thermal conductivity. Thermal recirculation reactor can be classified by parallel channels, porous medium, folded channel, spiral, etc. Inspired by this idea, the present combustion chamber employed a furnace with central reverse flame configuration similar to the thermal recirculation reactor with dual folded channel. At the same time, the present combustion systems were also developed in combining MILD combustion with the external exhaust gas recirculation to achieve ultra-low NOx emission. Its detail configuration can be seen in section 2 and Fig.2 of this paper. This configuration facilitates the intense mixing between the diluted oxidant stream and the high temperature flue gas stream inside the furnace in countercurrent manner. When the oxidant jet encounters the nature gas jet, the oxidant is in a state of high temperature and low oxygen, which can improve ignitability and also supply the hot diluted oxidant required by MILD combustion implement. Furthermore, the higher the external exhaust gas recirculation rate is, the lower oxygen concentration of the inlet oxidant is. Therefore, inlet velocity of the diluted oxidant also needs to increase to hold thermal power of the furnace constant. As a consequence, in-furnace turbulence intensity accordingly increases, which is helpful to suppress NOx formation.

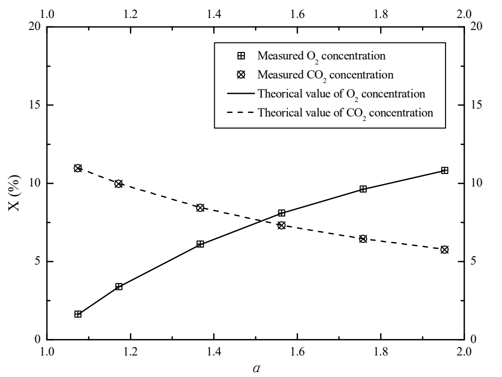

Fig.6. Comparison between the measured and theorical value when FGR equal to 0%.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202401_10(1).0009

4. Conclusion

To realize the goal of ultra-low NOx emission in boiler firing gas fuel, a novel MILD burner was developed based on the high external exhaust gas recirculation rate. Effect of the external exhaust gas recirculation rate on NOx emissions was studied in a pilot-scale furnace with thermal power of 700kW. The main conclusions are as follows:

(1) The proposed furnace configuration with central re-verse can promote mixing between the diluted oxidant stream and the exhaust gas stream inside the furnace in a countercurrent manner. This configuration is capable to supply substantial heat and mass recirculation to preheat the oxidant jet above self-ignition temperature and simultaneously dilute the reactant to create a low-oxygen environment.

(2) When no external exhaust gas recirculation is implemented, NOx emission for the traditional annular tube burner is in range of 150~371mg/m^3. Nevertheless, NOx emission for the MILD burner is in range of 71~134mg/m^3 under same thermal power, which is 30~40% lower than that of the traditional burner.

(3) NOx emission decreases with the increase of the external exhaust gas recirculation rate. When the external exhaust gas recirculation rate exceeds 30%, the limit NOx emission is about 40mg / m3, which can meet with the emission limit requirements of 50mg/m^3. When the external exhaust gas recirculation rate increases from 40% to 50%, NOx emission is in range of 8~28mg/m3.

References

[1] I. Glassman and R. A. Yetter, Combustion. 4th Ed., American Society of Mechanical Engineers, New York, USA, (2009).

[2] S. Sharma, A. Chowdhury and S. Kumar, A novel air injection scheme to achieve MILD combustion in a cantype gas turbine combustor. Energy, 194(2020) 1-13.

[3] T. Nikola, S. Mirjana and T. Vladimir, Effects of Flue Gas Recirculation on NOx Emissions from Gas-Fired Utility Boilers, Springer International Publishing, Zlatibor, Serbia (2021), 319-337.

[4] T. Plessing, N. Peters and J.G. Wünning, Laseroptical investigation of highly preheated combustion with strong exhaust gas recirculation, Symposium (International) on combustion, 27(2)(1998) 3197-3204.

[5] G. Wang, J. Si, M. Xu and J. Mi, MILD combustion versus conventional bluff-body flame of a premixed CH4/air jet in hot coflow. Energy, 187(2019) 1-16.

[6] A. Colorado and V. McDonell, Emissions and stability performance of a low-swirl burner operated on simulated biogas fuels in a boiler environment. Applied thermal engineering, 130(2018) 1507-1519.