Cost-benefit evaluation of different low NOx combustors of natural gas boilers in Beijing

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Abstract. This study focuses on establishing a cost-benefit evaluation model of low NOx combustion technology and the environmental benefits and economic benefits evaluation of technology operation were carried out as well. Results showed that: (1) The operation cost per unit calorific supply of the low NOx combustor with larger capacity (14 MW) boilers was 1.5-2.1 yuan/GJ, which was 22.3% to 26.2% as much as that of boilers with smaller capacity (0.7 MW). Compared with scattered boilers with smaller capacity, it is more economical to use boilers with larger capacity for centralized heating. (2) The lower the NOx emission concentration was, the greater the NOx emission reduction was. Furthermore, the lower the NOx emission benefits of low NOx combustor per unit calorific supply was, the greater the economic benefit of NOx reduction per unit calorific supply was. Based on the environmental and economic benefits analysis, the lean premixed combustor is recommended for natural gas boilers with capacity of 7 MW and below, and flue gas recirculation combustor (FGR-30) could be selected for natural gas boilers with capacity above 7 MW to achieve the NOx retrofits requirements of 30 mg/m^3 or 80 mg/m^3.

1 Introduction

In recent years, China's environmental air quality has improved significantly, but the control situation is still grim [1-4]. Industrial boiler industry is one of the major air pollution sources, and the national and local governments have introduced a number of measures, such as "replacing coal with gas", to reduce the emission of gaseous pollutants [5-8]. To implement the "clean air action plan" and continue to improve the atmospheric environmental quality, Beijing introduced a "boiler air pollutant emission standard" (DB11/139-2015) on July 1th, 2015, in which the NOx emission concentration was restricted below 80 mg/m^3, and that of new boiler was below 30 mg/m^3 [9]. The natural gas boiler of low nitrogen transformation work was required to complete before the year of 2019 within their respective jurisdictions, as to control the natural gas boiler NOx emissions in the city.

Many researchers had done research on the economic benefits of the controlling cost of air pollutants emitted from power station boilers and industrial boilers. For example, Yang et al. [14] obtained the operating cost of SCR system of typical units by constructing the operating cost evaluation system and calculation model of SCR system of coal-fired power plants. Shi [15] conducted the cost-benefit analysis for NOx control technology of flue gas from the coal-fired power stations, and established a cost-benefit evaluation system for denitration system. Liu et al. [16] also conducted the cost-benefit analysis on various fuel substitution measures for coal-fired industrial boilers. Furthermore, Zuo et al. [17] analyzed the environmental benefits of the air pollutant control systems applicable to China's coal-fired industrial boilers. Wu et al. [18] established a denitrification cost-benefit model with the capacity of coal-fired industrial boilers as the variable, and conducted the cost-benefit analysis on the heating boiler SCR denitrification technology. Feng [19] established an economic evaluation model of boiler capacity and denitrification efficiency by taking SCR and advanced reburning denitrification technologies as evaluation objects. Li et al. [20] proposed a method for calculating the benefit of pollutant emission reduction based on the traditional cost-benefit analysis model. Liu [21] analyzed the economic benefits of NOx reduction, such as health and agricultural production increase. Under the new environmental protection situation that the increasing proportion of natural gas-fired boilers and the increasing NOx emission requirements, the economic research of low nitrogen combustor for gas-fired boilers is still limited, but the economic evaluation of this technology still needs to be carried out.

Based on the method of cost-benefit analysis, the suitable analysis model of cost-benefit for natural gas boiler of low nitrogen combustor was set up. In addition, the operating cost and economic benefit of the four low nitrogen combustion technologies (fractional combustion technology, flue gas recycling technology (FGR) and lean premixed combustion technology [22]) were calculated which could provide reference for the choice of low nitrogen transformation technology route for

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natural gas boiler in the future and provides technical support for making and revising relevant economic policies.

2 Cost-benefit model of low nitrogen combustor for natural gas boilers

2.1 Operation cost model

2.1.1 Annual operating cost of NOx control equipment

The operating cost includes the fixed cost and variable cost. Among them, depreciation cost, maintenance cost and labor cost of low nitrogen combustor, the boilers with specific capacity and specific operating conditions are fixed, so it is called fixed cost. The material consumption cost will change as the operation time, NOx emission concentration and other influencing factors, which is entitled to variable cost. Depreciation costs mainly consists of equipment purchase cost, installation engineering cost and other depreciation costs, but also was affected by boiler capacity, NOx emission concentration, and so on. The maintenance cost is mainly referred to the equipment maintenance cost, which was affected by the same factors with depreciation cost. The number of operating personnel depends on the low nitrogen combustor. The annual salary of workers is affected by the regional economic level. The material consumption cost is related to the low nitrogen combustor, boiler capacity, NOx emission concentration, boiler load and the annual utilization hours. The material consumption price is also affected by the regional prices.

The depreciation cost is defined as:

$$D_t(q,c) = \frac{R}{n} \times TIC_t(q,c) \qquad (1)$$

The maintenance cost is defined as:

$$M_t(q,c) = \varepsilon \times \mathrm{TIC}_t(q,c) \qquad (2)$$

The labor cost is defined as:

$$L_{t,r} = m_t \times W_r \qquad (3)$$

The material consumption cost is defined as:

$$C_t = \sum_1^k M\, C_{k,r}(q,c,\eta,h) \times P_{k,r} \qquad （4）$$

The annual operating cost is defined as:

$$TAC_t(\mathrm{q},\mathrm{c},\upeta,\mathrm{h}) = D_t(\mathrm{q},\mathrm{c}) + M_t(\mathrm{q},\mathrm{c}) + L_{t,r} + C_t \qquad (5)$$

where $D_t(q,c)$ denotes the depreciation cost of low nitrogen combustor. t denotes the low nitrogen combustor. R denotes the formation rate of fixed assets. N denotes the equipment depreciation life. $TIC_t(q,c)$ denotes the equipment investment cost of low nitrogen combustor. q denotes the boiler capacity. c denotes the NOx emission concentration. C_t denotes the consumed material cost of low nitrogen combustor in operation. $M_t(q,c)$ denotes the maintenance cost of low nitrogen combustor. ε is the ratio of maintenance cost to investment cost. $L_{t,r}$ denotes the labor cost of low nitrogen combustor operating in area R. m_t denotes the operation and maintenance manual people number of low nitrogen combustion equipment. W_r denotes the annual salary of workers. $\sum_1^k M\, C_{k,r}(q,c,\eta,h)$ denotes the consumption of material K. $P_{k,r}$ denotes the price of consumed material K. h denotes the annual operating hour of the boiler. η denotes the boiler operating load. $TAC_t(\mathrm{q},\mathrm{c},\upeta,\mathrm{h})$ represents the annual operating cost of low nitrogen combustor.

2.1.2 Operating cost of per unit calorific supply

$$\mathrm{HC} = \frac{TAC_t(\mathrm{q},\mathrm{c},\upeta,\mathrm{h})}{q\times\mathrm{h}\times\alpha} \times 10^4 \qquad (6)$$

where HC refers to the operating cost of per unit calorific supply. α refers to the calorific value per unit operating load for boiler.

2.1.3 Unit NOx removal cost

$$\mathrm{PC} = \frac{TAC_t(\mathrm{q},\mathrm{c},\upeta,\mathrm{h})}{YR(\mathrm{q},\mathrm{c},\upeta,\mathrm{h})} \qquad (7)$$

$$\mathrm{YR}(\mathrm{q},\mathrm{c},\upeta,\mathrm{h}) = q \times u \times \eta \times h \times \left(\mathrm{EF} - c \times V_{gy} \times 10^{-2}\right) \times 10^{-4} \qquad (8)$$

where PC represents the cost of per unit NOx removal amount. $\mathrm{YR}(\mathrm{q},\mathrm{c},\upeta,\mathrm{h})$ represents the annual NOx removal amount for. u is the maximum amount of the natural gas consumption per unit hour. EF represents the NOx emission amount per unit volume of natural gas from the boiler without low nitrogen combustor. V_{gy} represents the volume of exhaust gas produced per unit volume of natural gas.

2.2 Benefit model

Benefit consists of environmental benefit and economic benefit that can be quantified as currency. Environmental benefit refers to the improvement effect on environmental quality through low nitrogen transformation of natural gas boiler, which is evaluated by the benefit of NOx emission per unit calorific supply. Economic benefit refers to the environmental degradation cost caused by the reduction of NOx emissions after low nitrogen transformation to natural gas boilers, including the benefit of reducing health economic losses, the benefit of reducing agricultural production losses and the benefit of reducing material economic losses [21], which is evaluated by the economic benefit of reducing NOx emissions per unit calorific supply.

2.2.1 Benefit of NOx emission per unit calorific supply

$$\mathrm{PEP} = \frac{YE(q,c,\upeta,\mathrm{h})}{q\times\hbar\times\alpha} \qquad (9)$$

$$\mathrm{YE}(q,c,\upeta,\mathrm{h}) = \mathrm{q} \times \mathrm{u} \times \upeta \times \mathrm{h} \times \mathrm{c} \times V_{gy} \qquad (10)$$

where PEP signifies the benefit of NOx emission per unit calorific supply. $\mathrm{YE}(q,c,\upeta,\mathrm{h})$ signifies the amount of the annual NOx emission.

2.2.2 Economic benefit of NOx emission reduction per unit calorific supply

$$\mathrm{HB} = \frac{TAB(q,c,\upeta,\mathrm{h})}{q\times\mathrm{h}\times\alpha} \qquad (11)$$

$$\mathrm{TAB}(\mathrm{q},\mathrm{c},\eta,\mathrm{h})=\mathrm{YR}(\mathrm{q},\mathrm{c},\eta,\mathrm{h})\times PB\times10^{-3}\quad(12)$$

where HB is the economic benefit of NOx emission reduction per unit calorific supply. $\mathrm{TAB}(\mathrm{q},\mathrm{c},\eta,\mathrm{h})$ represents the annual economic benefit of NOx emission reduction. PB means the economic benefit of NOx emission reduction per ton.

3. Benefit assessment of operation cost for the natural gas boilers equipped with the low nitrogen combustor

3.1 Data acquisition

In this study, the investment cost and operation cost of 100 natural gas hot water boilers were investigated. In addition, the NOx emission concentrations of each natural gas hot water boiler were monitored.

(1) After study, we found that the gas-fired boilers equipped with flue gas recycling technology (FGR-30) and lean combustion premix technology could meet NOx 30 mg/m^3 emission limit, and the staged combustion technology and flue gas recycling technology (FGR-80) technologies could meet NOx 80 mg/m^3 emission standard.

(2) The investment cost and material consumption cost of typical low nitrogen combustors were identified on the basis of the burner power of combustor. Based on the technical applicability and boiler capacity, the operating costs of different low nitrogen combustors are compared, as shown in **Table 1**， while the NOx emission concentrations of different low nitrogen combustors were shown in **Table 2**.

(3) After calculation and site investigation, the relevant parameters for boiler are as follows: 1) the annual operation time was 2880 h. 2) The operating load was 100%. 3) The daily weighted average value in Beijing was about 0.87 yuan/kW•h. 4) The average salary for employees during the heating period was 20 thousand yuan/person (obtained through research). 5) The formation percentage of fixed assets was 95%. 6) Equipment depreciation life was 15 years. 7) The ratio of maintenance cost to investment cost was 3%. 8) The calorific value per unit operating load for hot water boiler was 2.5 GJ/(t/h), and the converted value of hot water boiler output and heat was 3.6 GJ/MW. 9) The maximum gas consumption for steam boiler was 80 m^3/h, and the maximum gas consumption for hot water boiler was 70 m^3/h. 10) For natural gas boilers without low nitrogen technology, the NOx pollution factor EF was 18.71 kg/10^4 m^3 of natural gas [23]. 11) The standard gas volume V_{gy} was 12.3 m^3/m^3 natural gas [24]. 12) The economic benefit of a ton of NOx emission reduction was 18,248 yuan/ton of -NOx [21].

Table 1 Parameters of different low NOx combustors.

Boiler Capacity /MW	Ractional combustion technology		FGR-80		FGR-30		Lean premixed combustion technology		
	A	B	A	B	A	B	A	B	C
0.7	7.1	1.5	10.2	3	13.8	3	18.1	4	0.2
1.4	9.2	3	12.6	5.5	16.2	5.5	20.7	5.5	0.2
2.8	13.7	7.5	14.8	11	23.2	11	33.1	11	0.2
4.2	16.4	11	17.4	15	29.8	15	42.1	18.5	0.3
5.6	23.1	15	24.8	18.5	36.8	18.5	58.4	22	0.5
7	29.8	18.5	29.1	37	42.1	37	64.2	37	0.5
10.5	41.2	37	44.3	55	68.4	55	-	-	-
14	53.0	55	61.1	75	86.5	75	-	-	-

Note: A represents the investment cost (10^4 yuan), B denotes the blast blower power (kW), and C means the material cost (10^4 yuan).

Table 2 NOx emission concentrations of different low NOx combustors.

Types of technologies	Fractional combustion technology	FGR-80	FGR-30	Lean premixed combustion technology
Number	100	100	100	100
NOx emission concentrations（mg/m^3）	35~98	60~89	16~30	6~30
Average NOx emission concentrations（mg/m^3）	69	76	26	17

3.2 Assessment of operation cost

3.2.1 Assessment of operation cost of per unit calorific supply of low nitrogen combustor

As shown in **Figure 1**, after the low nitrogen transformation of boilers under 7 MW, the operating cost per calorific supply of the lean combustion premix natural gas boilers was the highest with the value was 2.5~9.4 yuan/GJ, which was 1.3~1.7 times as much as that of fractional combustion natural gas boilers. Meanwhile, lean combustion premix natural gas boiler has the highest material consumption cost and running cost. The combustors and blast blowers of boilers below 7 MW are integrated, while the combustors and blast blowers of the boilers above 7 MW are split, resulting in the difference in the investment cost of the equipment. As a result, the operating cost per unit calorific supply of lean premixed combustor and FGR combustor firstly tended to decrease, subsequently it increased and later decreased. Therefore, under the same operating cost per unit calorific supply, it is advisable to adopt the fractional combustion technology to meet the NOx emission requirements of 80 mg/m^3, and to adopt the flue gas recycling technology (FGR-30) to meet the NOx emission requirements of 30 mg/m^3. The operating cost per unit calorific supply of 14 MW boiler equipped with low nitrogen combustor was 1.5-2.1 yuan/GJ, which was 22.3%~26.2% as much as that of 0.7 MW boiler. That is, compared with dispersed small capacity boilers, adopting centralized heating with larger capacity boilers is more economical in the cost.

https://doi.org/10.1051/e3sconf/202123601021

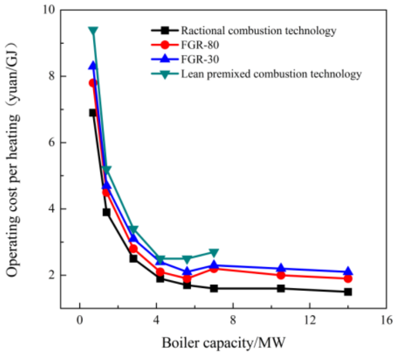

Figure. 1 Operation cost of unit calorific supply of different low nitrogen combustors.

3.2.2 Cost assessment of per unit NOx removal of low nitrogen combustor

As shown in **Figure. 2**, the per unit NOx removal cost of FGR-30 was the lowest (48.7~192.6 yuan/kg), while the per unit NOx removal cost of fractional combustion technology was the highest (54.4~243.4 yuan/kg), which was 1.3~1.7 times of FGR-30 technology. Therefore, under the same per unit NOx removal cost and the boiler capacity, FGR-30 technology is recommended to meet emission requirements of NOx 80 mg/m^3 or 30 mg/m^3. Furthermore, it could be clearly seen that the per unit NOx removal cost of the four low nitrogen combustor decreased with the increment of boiler capacity. For example, the per unit NOx removal cost of 5.6 MW boiler decreased by 71.1%~73.7% than that of 0.7 MW boiler, suggesting that the decline range was very large. While the per unit NOx removal cost of 5.6 MW boiler decreased by 9.4%~18.3%, suggesting that the decline range was relatively small. Hence, we concluded that, under the identical per unit NOx removal costs, the boiler with larger capacity is beneficial to reduce the NOx emission, but the change range is very slight.

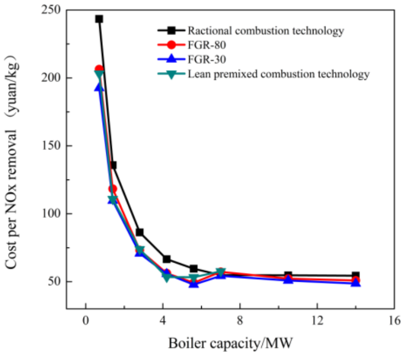

Figure. 2 Per unit NOx removal cost of different low nitrogen combustors.

3.3 Environmental benefit and economic benefit assessment

The NOx emission benefits per unit calorific supply for different low NOx combustion technologies are listed in **Table 3**. As can be seen, the NOx emission benefit per unit calorific supply was the smallest for lean premix natural gas boiler (34~72 mg/GJ), which was approximately 0.15~0.25 times as much as that of fractional combustion boiler (222~290 mg/GJ). As discussed above in **Table 2**, among the four low nitrogen combustion technologies, the NOx emission concentration from the lean premix natural gas boiler was the lowest. Therefore, it could conclude that the lower the concentration of NOx emission was, the greater the reduction of NOx emission was, and the lower the NOx emission benefit per unit calorific supply of low nitrogen combustor was, the higher the environmental benefit was. In addition, when the per unit heat quantity of NOx emissions benefit value are identical, in order to achieve the NOx emissions limits, the lean premixed combustion technology could be selected for natural gas boilers with capacity of 7 MW and below, and flue gas recirculation (FGR-30) could be selected for natural gas boilers with capacity above 7 MW regardless of the NOx retrofits requirements of 30 mg/m^3 or 80 mg/m^3.

As illuminated in **Table** 4, the economic benefit of NOx emission reduction per unit calorific supply of different low NOx combustion technologies showed the similar trends as the environmental benefit. This indicates economic benefit correlates positively environmental benefit.

Table 3 NOx emission benefit of per unit calorific supply of different low NOx combustion technologies.

Environmental benefit	Fractional combustion technology	FGR -80	FGR -30	Lean premixed combustion technology
Minimum (mg/GJ)	222	205	68	34
Maximum (mg/GJ)	290	273	103	72
Mean (mg/GJ)	236	260	89	58

Table 4 Economic benefit of NOx emission reduction per unit calorific supply of different low NOx combustion technologies.

Economic benefit	Fractional combustion technology	FGR -80	FGR -30	Lean premixed combustion technology
Minimum (mg/GJ)	0.42	0.39	0.76	0.82
Maximum (mg/GJ)	0.54	0.57	0.82	0.89
Mean (mg/GJ)	0.52	0.47	0.79	0.84

4 Conclusions

The cost-benefit evaluation model was established in this study based on the low nitrogen combustor for natural gas boilers in Beijing. The main conclusions are as follows:

(1) As the boiler capacity increases, the investment cost per unit capacity decreases. Although the variable cost per unit time increases, the operating cost per unit calorific supply decreases. Compared with small-capacity boilers, it is more economical to adopt the large-capacity boilers for centralized heating.

(2) When the operating cost per unit calorific supply is equal, it is advisable to choose the fractional combustion technology to meet the NOx emission requirements of 80 mg/m^3, and to choose the flue gas recycling technology (FGR-30) to meet the NOx emission requirements of 30 mg/m^3. When the cost of per unit NOx removal and the boiler capacity are the same, FGR-30 is recommended to meet emission requirements of NOx 80 mg/m^3 or 30 mg/m^3.

(3) In order to achieve higher environmental and economic benefits, the lean premixed combustion technology could be selected for natural gas boilers with capacity of 7 MW and below, and flue gas recirculation (FGR-30) could be selected for natural gas boilers with capacity above 7 MW to achieve the low NOx retrofits requirements of 30 mg/m^3 or 80 mg/m^3.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (No. 2016YFC0203701), the Youth Core Plan (YC201810) and the Youth Talent Plan (K113-08-04).

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