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Combustion Air Humidification for NO_x Emissions Reduction in Gas Boiler: An Experimental Study

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ABSTRACT

NO_x emission reduction from gas boilers has become a key issue in improving air quality. Combustion air humidification technology is gradually being used to reduce NO_x emissions. However, the NO_x emission reduction effect of gas boilers at a higher combustion air humidity has been studied less. A flue gas with low NO_x emissions and a waste heat recovery system using combustion air humidification technology are proposed in this study. In the ultra-low NO_x mode, the effect of high combustion air humidity on NO_x emission reduction and efficiency of the gas boiler were studied experimentally. In the waste heat recovery mode, the effects of the heat network backwater temperature on the NO_x emission reduction and system efficiency were studied experimentally. Results showed that an increase in air humidity can significantly reduce the NO_x concentration formed by combustion. The ultra-low NO_x mode reduces NO_x emissions from 130 mg/m³ to 23.3 mg/m³ and affects the boiler efficiency slightly. In the waste heat recovery mode, NO_x emissions can be reduced to 39.9 mg/m³ when the backwater temperature of the heat network is 55 °C. This condition improves the efficiency to 93.8%. The analysis results provide suggestions for the selection of the operation modes.

Introduction

The thermal efficiency of gas-fired heating boilers is higher than that of coal-fired boilers. Compared to coal, natural gas is regarded as a cleaner energy source with less carbon emissions and air contamination in the combustion process [1]. Gas boiler combustion produces nitrogen oxides (NO_x), which generate fog and haze [2]. NO_x, which has a significant impact on the atmosphere, mainly refers to a variety of nitrogen and oxygen compounds, namely NO, NO₂, N₂O, N₂O₃, N₂O₄, and N₂O₅ [3]. Acidifying substance emissions damage human health, ecosystems, buildings, and materials [4]. Boilers that heat buildings emit large amounts of NO_x. Thus, improving air quality and developing clean heating are of great significance. Cities, such as Beijing, Tianjin, and Zhengzhou, have introduced strict local standards. However, majority of the existing boilers exceed these standards

and cannot be used. Therefore, nitrogen oxide emission reduction technology for gas boilers has become a hot issue in the industry.

Generally, an increase in furnace temperature promotes NO_x production. Recently, humidification combustion technology has been used to reduce NO_x production because of its ability to lower the combustion temperatures. This technology was first used for engines and gas turbines. Wu et al. [5] investigated the effect of water-spraying technology on the combustion and emission characteristics of heavy natural gas engines through numerical simulations. According to the simulation results, an increase in spray mass decreases the flame propagation speed, reduces the rate of fuel heat release, extends the duration of combustion, and decreases the maximum temperature. This behavior significantly reduces the thermal engine load and inhibits NO_x production. Jonsson and Yan [6] summarized the study of humidified gas turbine

Nomenclature

a	estimated standard deviation of the mean distribution	T_a	combustion air temperature ($^{\circ}\text{C}$)
BEVP	boiler equipped with a vapor pump	T_b	backwater temperature of the heat network, ($^{\circ}\text{C}$)
B	natural gas consumption (Nm^3/h)	T_H	supply water temperature of the heat network ($^{\circ}\text{C}$)
CNY	Chinese Yuan	T_{FI}	flue gas temperature of boiler ($^{\circ}\text{C}$)
C_m	mass concentration (mg/m^3)	T_s	spray temperature of exchanger B ($^{\circ}\text{C}$)
C_m, NO_x	NO_x mass concentration	T_w	backwater temperature of the heat network after preheating ($^{\circ}\text{C}$)
CN	hydrocyanic acid root	ULN	ultra-low NO_x emission
c_p	constant pressure specific heat of water ($\text{kJ}/(\text{kg}\cdot\text{K})$)	u_1	uncertainty caused by repeated measurement of NO
$C_{PPM, \text{NO}}$	PPM concentrations of NO	u_2	uncertainty caused by repeated measurement of NO_2
C_{PPM, NO_2}	PPM concentrations of NO_2	u_3	uncertainty caused by an error in the flue gas analyzer
CO	carbon monoxide	u_c	combined standard uncertainty
FGLNHR-CAH	flue gas low NO_x emission and waste heat recovery system using combustion air humidification technology	u_i	a component of uncertainty
F_s	spray flow (m^3/h)	u_{xi}	measurement standard uncertainty
$\partial f/\partial x_i$	the transfer coefficient of the effect of u_{xi} on the measured estimate	ν	degrees of freedom
H_a	combustion air humidity (g/kg Dry air)	V_m	molar volume of gas
HCN	hydrogen cyanide	WHR	waste heat recovery
LGR	liquid gas ratio of exchanger B	x	arithmetic mean value
m	mass flowrate of heat network (kg/s)	x_i	measured value
M_{NO_2}	relative molecular mass of NO_2		
n	number of measurements		
N	nitrogen atoms	Greek symbols	
NO	nitric oxide	φ	uncertainty
NO_2	nitrogen dioxide	σ	estimated value of the standard deviation of a single measurement
NO_x	nitrogen oxide	σ_u/u	relative standard deviation of u
N_2	nitrogen	η_{Boiler}	boiler efficiency
$N_2\text{O}$	nitrous oxide	η_{Total}	total system efficiency
$N_2\text{O}_3$	dinitrogen trioxide		
$N_2\text{O}_4$	dinitrogen tetroxide		
$N_2\text{O}_5$	nitrogen pentoxide		
O	oxygen atom	Subscripts	
O_2	oxygen	a	combustion air
OH	hydroxide ion	b	backwater
Q_{out}	output heat of gas boiler (kJ/Nm^3)	in	input
Q_{in}	input heat of gas boiler (kJ/Nm^3)	out	output
$Q_{net,ar}$	low calorific value of natural gas (kJ/Nm^3)	s	spray water
Q_w	waste heat recovery quantity (kJ/Nm^3)		

combustion and proposed that humidification reduces the generation of NO in the combustion process.

As humidification technology has been proven to achieve NO_x reduction in engines and gas turbines, researchers have applied humidification technology to gas boilers. However, humidification combustion reduces boiler efficiency [7]; therefore, thermal efficiency should be considered. Waste heat recovery (WHR) can improve the energy utilization rate and reduce energy waste [8–12]. Compared to other fuels, natural gas combustion produces more water vapor. Hence, there is more latent heat in the flue gas to recover [13, 14]. Therefore, researchers have mostly used WHR technology to improve thermal efficiency when utilizing humidification technology.

Lee et al. [15] used condensed water to humidify air. When the air temperature was low, the moisture

content in the saturated state was low. The system uses condensate water to humidify the furnace directly so that the system can achieve higher moisture content conditions. Generally, boiler efficiency under spray technology has been studied, and no specific study on NO_x has been conducted. Wang et al. [16] proposed a boiler equipped with a vapor pump (BEVP) system, which humidifies the combustion air. Although the heat transfer characteristics of the BEVP system have been studied, NO_x emission reduction has not been studied. Chen et al. [7, 17] proposed a new non-contact total heat exchanger to supply air and flue gas for heat recovery. Additionally, they studied the influence of air humidification on the efficiency and emissions of the boiler. The research findings showed that air humidification improved the overall boiler efficiency and reduced NO_x concentration.

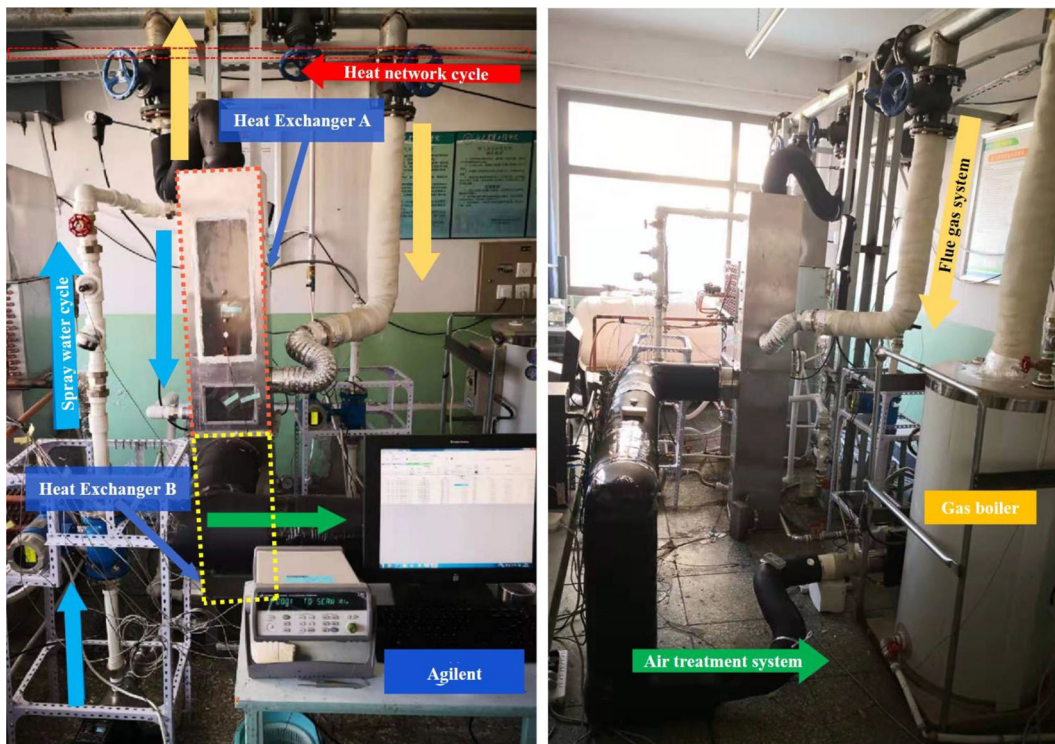


Figure 1. FGLNHR-CAH system experiment bench.

However, the maximum air humidity in their study was $48 \text{ g/kg}_{\text{Dry air}}$ and higher air humidity conditions were not considered. Zhang et al. [18] proposed an exhaust gas condensation heat recovery system that synergized with a low nitrogen oxide discharge system. However, the factors influencing NO_x emission reduction were not explained. Men et al. [19] proposed a new flue gas WHR system equipped with an enthalpy wheel, which was used to recover the waste heat and water of the flue gas. They studied the effect of system air humidification but did not study the effect of NO_x emission reduction.

In the aforementioned studies, the NO_x reduction effect of gas boilers at higher combustion air humidity has not been studied extensively. Moreover, majority of systems use flue gas waste heat to heat humidified combustion air, and there is competition between the waste heat used to heat the air and the recycled waste heat, which affects the NO_x emission reduction of the system. However, the effect of flue gas WHR on NO_x emission reduction has not yet been studied in detail.

A flue gas with low NO_x emissions and a WHR system using combustion air humidification technology were proposed (FGLNHR-CAH). Additionally, ultra-low NO_x (ULN) emission and WHR modes were proposed. The efficiency and NO_x emission reduction effects of gas boilers under high air humidity were also investigated. Subsequently, the effect of WHR on the NO_x reduction effect and system efficiency was

studied, and the mechanism of NO_x emission reduction by air humidification and the economic applicability of different operation modes were discussed.

Experimental

System description

The experimental system of FGLNHR-CAH was composed of a gas boiler, water tank, direct contact heat exchangers A and B, plate heat exchanger, and water pump, as shown in Fig. 1. Heat exchanger B was the core equipment used for heating and humidifying the combustion air. The specific parameters of the experimental flue gas, which was obtained from a 58 kW vertical gas boiler, are listed in Table 1.

The operating mode of the system could be adjusted using a valve. In the ULN mode, valves b and c are closed, and valves a and d are opened. In the WHR mode, valves a and d are closed, and valves b and c are opened. The system flow chart is shown in Figs. 2 and 3. The experimental system consisted of four parts: the flue gas system, air treatment system, spray water cycle, and heat network cycle.

ULN mode:

1. Flue gas system: The flue gas system consisted mainly of a gas boiler and a direct contact heat exchanger. The high-temperature flue gas was

discharged from the boiler and through the pipeline into heat exchanger A, which was a spray-type heat exchanger with flue gas and sprayed water to exchange heat and mass. The flue gas was passed through a screen mist remover to remove moisture, which discharged into the atmosphere.

2. Air treatment system: Direct contact heat exchanger B was the core equipment. The water in the water storage tray of heat exchanger A directly enters heat exchanger B as spray water heating and humidifying combustion air. To prevent excess water from entering the burner, a screen defogging device was set at the exit of heat exchanger B.
3. Spray water cycle: Spray water is the main medium for heat transfer in the system. The low-temperature spray water and high-temperature flue gas achieved a complete heat exchange in heat exchanger A. After the low-temperature spray water was heated, the water pump was fed into heat exchanger B to exchange heat and mass with the combustion air. Finally, the spray water in heat exchanger B was returned to heat exchanger A.

4. Heat network cycle: The hot water in the boiler was supplied to the thermal user and returned to the boiler for further heating.

WHR mode:

The flow of the flue gas and air treatment systems was the same as that in the ULN mode.

1. Spray-water cycle: After being heated by the flue gas in heat exchanger A, the spray water first enters the plate heat exchanger to heat the heat network return water. Then, it enters heat exchanger B to humidify the combustion air. Finally, it returns to heat exchanger A to exchange heat with the flue gas.
2. Heat network cycle: Hot water in the boiler was supplied to the thermal user. The heat network backwater entered the plate heat exchanger first and then returned to the boiler for further heating.

Additional operating parameters of this system are listed in Table 2.

Table 1. Boiler operating parameters.

Parameters	Unit	Value
Boiler heat capacity	kW	58
Natural gas consumption	Nm ³ /h	5.7
Excess air ratio	—	1.2
Boiler load	%	90
Flue gas temperature	°C	205.8
Flow rate of boiler water supply	L/min	31
Original boiler efficiency	%	87.5

Test methods

The distribution of the measurement points in this experimental platform is shown in Fig. 2, and the test equipment is listed in Table 3. The main test instruments included an electromagnetic flowmeter, flue gas analyzer, temperature and humidity recording instrument, electromagnetic flowmeter, and thermocouple. An Agilent data-acquisition module was used as the

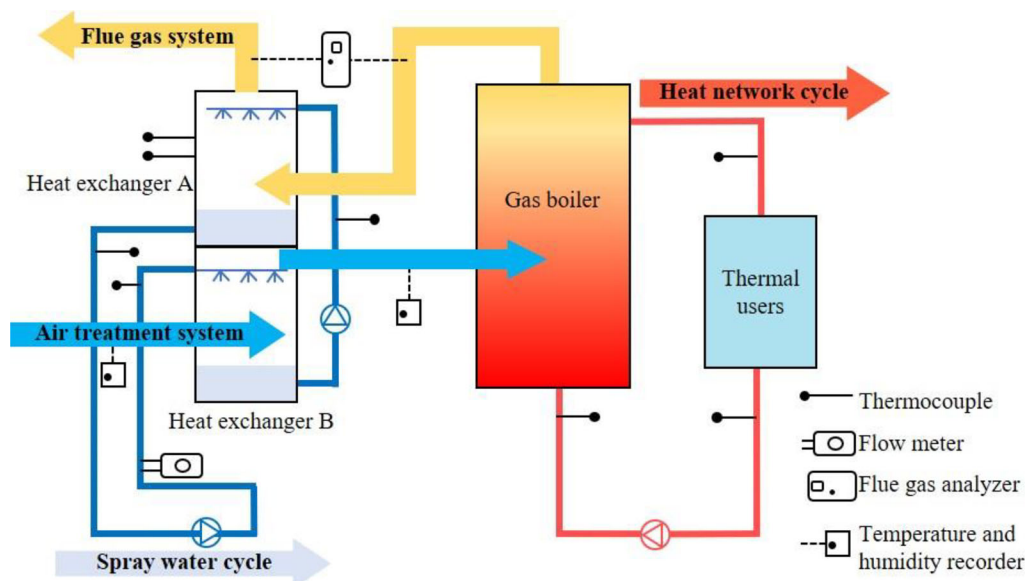


Figure 2. Flow chart of ULN mode of FGLNHR-CAH system.

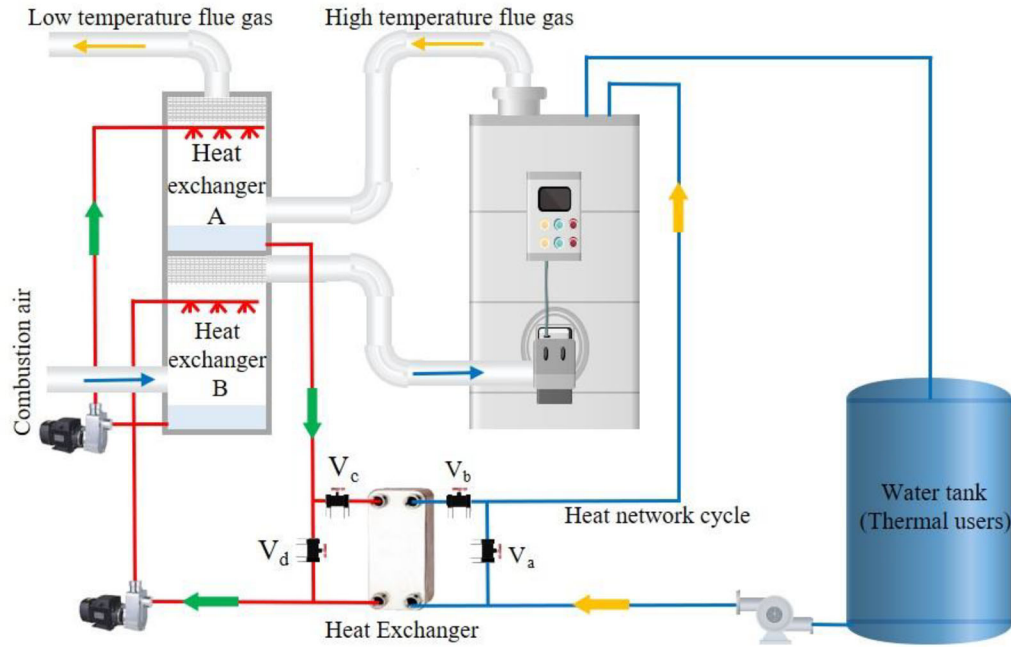


Figure 3. Flow chart of WHR mode of FGLNHR-CAH system.

Table 2. Operating parameters of the FGLNHR-CAH system.

System	Mode	T_s	T_b	F_s						
		°C	°C	m ³ /h						
FGLNHR-CAH	ULN mode	59.6	—	0.21	0.35	0.43	0.54	0.65	0.74	0.84
	WHR mode 1	54.7	55	0.23	0.34	0.41	0.52	0.63	0.74	0.82
	WHR mode 2	49.9	50	0.24	0.36	0.43	0.54	0.63	0.74	0.82
	WHR mode 3	45.8	45	0.25	0.35	0.43	0.54	0.64	0.73	0.83

Table 3. Details of the test equipment.

Parameter	Equipment	Model	Accuracy
Flue gas temperature	Flue gas analyzer	Testo340	±0.5%(reading)
NO concentration	Flue gas analyzer	Testo340	±5 ppm (0-99 ppm)
NO ₂ concentration	Flue gas analyzer	Testo340	±10 ppm (0-199 ppm)
Water temperature	Thermocouple	T-type thermocouple	±0.3 °C
Spray water flow	Electromagnetic Flowmeter	LDYD3-032-16-1-1	±0.5%(reading)
Air temperature	Temperature and humidity recorder	WWSZY-1	±0.3 °C(-50-100 °C)
Air humidity ratio	Temperature and humidity recorder	WWSZY-1	±2%RH (reading)
Air velocity	Digital Anemometer	AS8336	±0.03 m/s (0.3-45 m/s)

experimental platform. Data was recorded every 5 s when the system was running stably. In total, 240 sets of data were measured for each condition.

Uncertainty analysis

According to the methods described in error theory and data processing [20], the primary sources of uncertainty when measuring the NO_x concentration were analyzed, and the standard uncertainty that resulted from all types of elements was tested using a detailed direct evaluation method.

In case of uncertainties, errors exist between the test data and truth value. Herein, the uncertainty propagation of the measurement and experimental data are analyzed theoretically. Hence, the direct error analysis method was calculated using:

$$\varphi = \frac{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2}}{n(n-1)} \quad (1)$$

where φ refers to the uncertainty, n is the number of data tests, and x_i is the data value of the i^{th} measurement. \bar{x} denotes the arithmetic average of the experimental data in each group in the form of:

Table 4. Uncertainty calculation equation [20].

Purpose	Uncertainty equation
Standard deviation	$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}}$ (3)
Measurement standard uncertainty The assessment method of class A (n times)	$u_{x_i} = \sigma_i / \sqrt{n}$ (4)
Measurement standard uncertainty The assessment method of class B (uniform distribution)	$u_{x_i} = a / \sqrt{3}$ (5)
Degrees of freedom (The assessment method of class A)	$\nu = n - 1$ (6)
Degrees of freedom (The assessment method of class B)	$\nu = \frac{1}{2 \left(\frac{\sigma_u}{u} \right)^2}$ (7)
A component of uncertainty	$u_i = \left \frac{\partial f}{\partial x_i} \right u_{x_i}$ (8)
Combined standard uncertainty	$u_c = \sqrt{\sum_{i=1}^n u_i^2}$ (9)

$$\bar{x} = \sum_{i=1}^n x_i / n \quad (2)$$

Using the same method, an uncertainty analysis was performed for all operating conditions. The main calculation equations are listed in Table 4, see equations (3) - (9). To avoid random error, all the measurements were repeated 5 times with equal accuracy to determine the error margin.

The mass concentration of NO_x was calculated according to NO₂, and the equation is as follows:

$$C_{m,NO_x} = \frac{M_{NO_2}(C_{PPM,NO} + C_{PPM,NO_2})}{V_m} \quad (10)$$

The calculation considers H_a = 49 g/kg_{dry air} in WHR mode 1 as an example. The calculated arithmetic mean was 22.36 ppm for NO and 4.87 ppm for NO₂. The estimated amount of NO_x according to equation (10) was 55.91 mg/m³.

The main factors that had a significant influence on the NO_x measurement uncertainty were as follows: uncertainties u₁ and u₂ were caused by the measurement repeatability of NO and NO₂, respectively, and uncertainty u₃ was caused by an error in the flue gas analyzer. According to an analysis of these uncertainty characteristics, the assessment method of class A was used for uncertainties u₁ and u₂, whereas that of class B was used for uncertainty u₃.

By calculation, the standard uncertainty components that were caused by the measurement repeatability of NO and NO₂ were 0.61 mg/m³ (239 degrees of freedom) and 0.17 mg/m³ (239 degrees of freedom), respectively. The standard uncertainty component caused by the value error of the flue gas analyzer was 13.26 mg/m³ according to Equations (5) and (8). The relative standard deviation was 10% and the corresponding degree of freedom was calculated to be 50 using Equation (7). Uncertainties u₁, u₂, and u₃ were

independent, and the combined standard uncertainty was 13.28 mg/m³. The final measurement of NO_x was 55.91 ± 13.28 mg/m³. The errors of the other parameters are similar to those in the abovementioned analysis.

Performance evaluation index

The performance evaluation indicators were defined. The output heat of the gas boiler (Q_{out}), input heat of the gas boiler (Q_{in}), WHR quantity (Q_w), boiler efficiency (η_{Boiler}), and the total system efficiency (η_{Total}) are expressed as follows:

$$Q_{out} = c_p m (T_H - T_b) \quad (11)$$

$$Q_{in} = B \cdot Q_{net,ar} \quad (12)$$

$$Q_w = c_p m (T_w - T_b) \quad (13)$$

$$\eta_{Boiler} = \frac{Q_{out}}{Q_{in}} \quad (14)$$

$$\eta_{Total} = \frac{Q_{out} + Q_w}{Q_{in}} \quad (15)$$

where c_p is the constant pressure specific heat of water, kJ/(kg·K); m is the mass flow rate, kg/s; T_H is the supply water temperature of the heat network, °C; T_b is the backwater temperature of the heat network, °C; B is the natural gas consumption, Nm³/h; Q_{net,ar} is the low calorific value of natural gas, kJ/Nm³; and T_w is the backwater temperature of the heat network after preheating, °C.

Results

In this section, we present the results of the combustion experiments. The influence of combustion air humidity on system performance (boiler efficiency, NO_x emissions, NO_x emission stability, etc.) was

studied. The effect of the WHR mode on the NO_x emissions and total system efficiency was also studied.

Effect of combustion air humidity on gas boiler efficiency

Boiler efficiency is an important system evaluation index. Boiler efficiency can be calculated using Eq. (14). In the experiment, the temperature and humidity of the combustion air were increased simultaneously, and the boiler efficiency was affected by two factors. After numerous tests, the average efficiency of the experimental boiler without the FGLNHR-CAH system was 87.5%. After being added to the system, with the increase in combustion air humidity, the change in boiler efficiency did not show an obvious rule, but most of the test results were slightly lower than the original boiler efficiency, as shown in Fig. 4. The average efficiency of the system decreased by 0.7% with FGLNHR-CHA.

Effect of combustion air humidity on NO_x emissions

Combustion air with different humidity was directed into the burner to study the effect of air humidity on NO_x concentration in the flue gas. For comparison, the NO_x emission concentration of the boiler under non-humidification conditions was tested experimentally. Under this condition, the air humidity was $3.2 \text{ g/kg}_{\text{Dry air}}$ and the NO_x concentration in the flue gas reached 130 mg/m^3 .

The NO_x concentration of the system was reduced to 58.7 mg/m^3 by humidifying air to $38.9 \text{ g/kg}_{\text{Dry air}}$. When the air humidity increased to $101.2 \text{ g/kg}_{\text{Dry air}}$, the NO_x in the flue gas was reduced to 23.3 mg/m^3 .

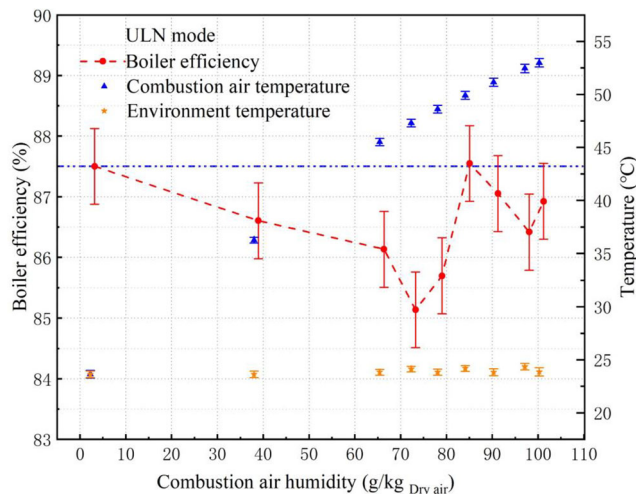


Figure 4. Effect of air humidity on boiler efficiency (ULN mode).

The NO_x emission reduction effect was better under high air humidity conditions. According to the experimental results, the NO_x concentration gradually decreased with an increase in air humidity, as shown in Fig. 5.

Effect of combustion air humidity on NO and NO_2 concentration

The NO_x in the gas boiler flue gas was composed mainly of NO and NO_2 . The results show that the NO concentration in the flue gas decreases significantly with an increase in humidity in the combustion air, but the concentration of NO_2 increases slightly, as shown in Fig. 6. According to the formation mechanism of NO_x (discussed in detail in the next section), the thermal NO_x formed by gas combustion was composed mainly of NO . Combustion air humidification technology reduced the generation of thermal NO_x ; thus, the NO production in the experiment decreased significantly. Through experiments and numerical simulations, Wang et al. [21] found that within a certain temperature range, a lower thermal combustion product temperature resulted in a higher likelihood of NO_2 generation. Combustion air humidification technology can reduce the furnace temperature [22]; therefore, a decrease in temperature results in an increase in NO_2 concentration in the flue gas.

Effect of combustion air humidity on NO_x emission stability test

When the system was running steadily, NO_x concentration was tested every 5 s, and the NO_x emissions is determined as shown in Uncertainty Analysis ($55.91 \pm 13.28 \text{ mg/m}^3$). Each working condition was tested for at least 20 min.

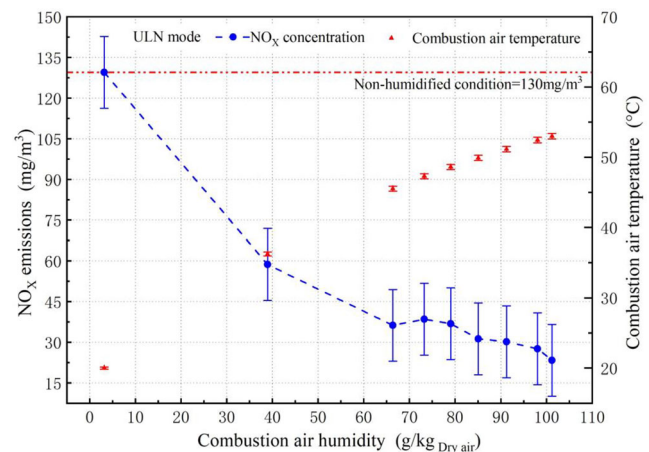


Figure 5. Effect of air humidity on NO_x emissions (ULN mode).

The NO_x emissions under different combustion air humidity conditions in WHR mode 1 are shown in Fig. 7. It can be seen that although the NO_x concentration fluctuates, the fluctuation range is small. The stability of NO_x emissions can be reflected intuitively. The standard deviations for the six working conditions were 0.424, 0.634, 0.940, 0.471, 0.478, and 0.496, respectively. These values are small and can reflect the stability of NO_x emissions.

Effect of flue gas WHR on NO_x emission

In this section, we describe the effect of WHR on the NO_x emission concentration in the system. The

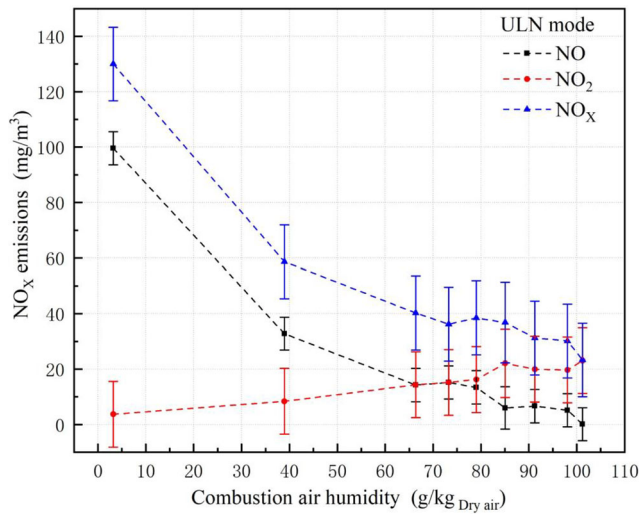


Figure 6. Effect of air humidity on NO and NO_2 emissions (ULN mode).

temperature of the flue gas discharged by the system is shown in Fig. 8. The flue gas temperature of the original boiler was 205.8°C . The FGLNHR-CAH system can reduce the flue gas temperature to less than 100°C under all operating conditions. Additionally, with an increase in the spray water flow of heat exchanger A, the flue gas temperature decreased gradually. The flue gas temperature in WHR mode 3 is the lowest and can be reduced to 51.5°C .

For NO_x emission reduction, the most essential difference between the different operation modes is the spray water temperature in heat exchanger B, which directly affects the combustion air temperature. The liquid gas ratio (LGR) of heat exchanger B is the ratio of the mass flow rate of the spray water to the mass

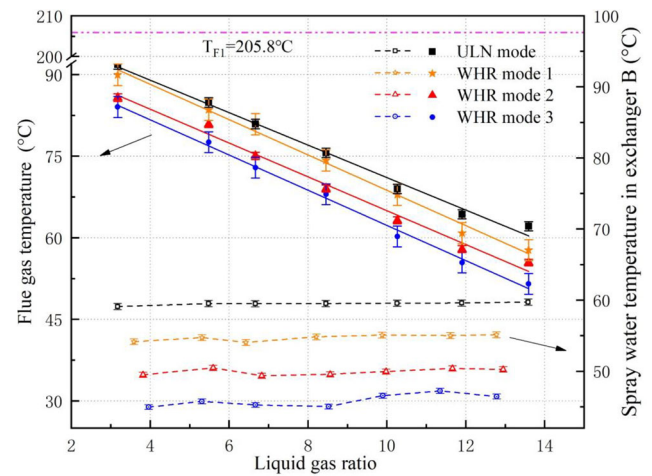


Figure 8. Effect of LGR on spray water temperature in exchanger B and flue gas temperature.

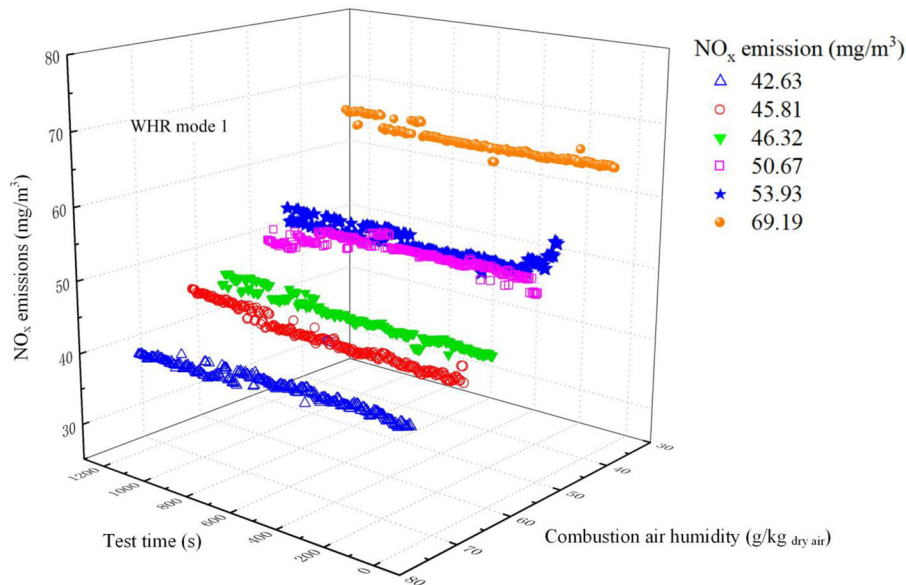


Figure 7. NO_x emission stability test for different air humidity in WHR mode 1.

flow rate of air. In the ULN mode, the average temperature of the spray water was 59.6°C . In the WHR mode, the backwater temperatures of the heat network were 45, 50, and 55°C . According to the system process, the backwater temperature of the heat network directly affected the spray temperature of heat exchanger B. The average temperatures recorded in the WHR mode were 54.7, 49.9, and 45.8°C , as shown in Fig. 8.

For a certain airflow rate, LGR was improved by increasing the spray flow rate. With an increase in LGR, the combustion air temperature increased nonlinearly. For the same LGR, a higher spray water temperature results in a higher combustion air temperature, as shown in Fig. 9. With an increase in

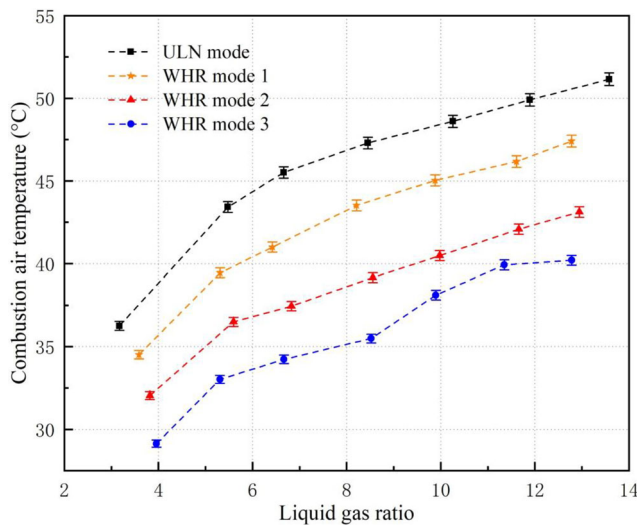


Figure 9. Effect of LGR on combustion air temperature.

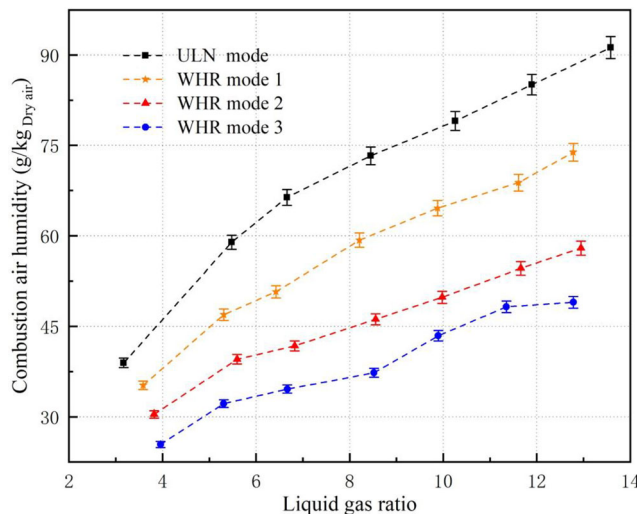


Figure 10. Effect of LGR on combustion air humidity.

LGR, the combustion air humidity increased nonlinearly, and the increasing trend slowed gradually, as shown in Fig. 10. The maximum combustion air humidity was different for different operation modes. The reason for this phenomenon is the effect of air temperature on saturation. Higher temperatures result in higher air saturation [23]. The ULN mode without WHR had the highest spray water temperature; therefore, the combustion air temperature and humidity were the highest for the same LGR. In the actual operation mode, the maximum combustion air humidity was $101.2\text{ g/kg}_{\text{Dry air}}$.

The NO_x emission concentration and total efficiency of the system in different operating modes were experimentally tested. Under different modes, the maximum combustion air humidity was different; therefore, the effect of NO_x emission reduction and total efficiency varied, as shown in Figs. 11 and 12.

In WHR mode 3, the maximum combustion air humidity was $49\text{ g/kg}_{\text{Dry air}}$, NO_x emissions were 50 mg/m^3 , and total efficiency was 96.6%. In WHR mode 2, the maximum combustion air humidity was $57.9\text{ g/kg}_{\text{Dry air}}$, NO_x emissions were 46.4 mg/m^3 , and total efficiency was 94.1%. In WHR mode 1, the maximum combustion air humidity was $73.8\text{ g/kg}_{\text{Dry air}}$, NO_x emissions were 39.9 mg/m^3 , and the total efficiency was 93.8%. In the ULN mode, the maximum combustion air humidity was $101.2\text{ g/kg}_{\text{Dry air}}$, NO_x emissions were 23.3 mg/m^3 , and the total efficiency was 86.9%.

Therefore, the NO_x emission reduction effect of the ULN mode is the best, but it affects boiler efficiency. The WHR mode can also reduce NO_x emissions, and the emission reduction effect is not as good as that of the ULN mode. However, the system efficiency improved through WHR.

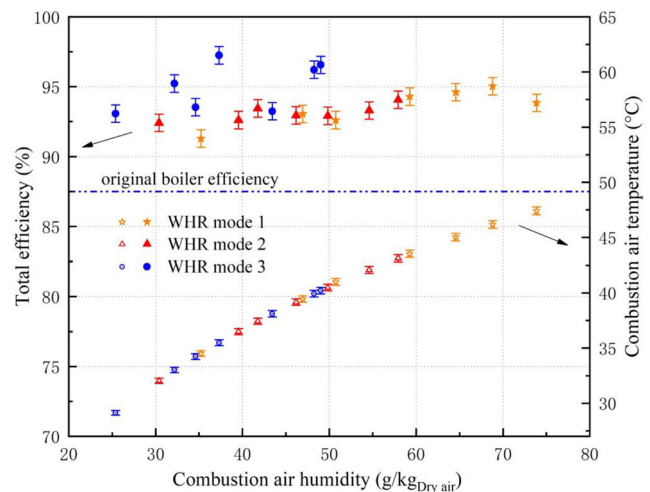


Figure 11. Effect of air humidity on the total efficiency.

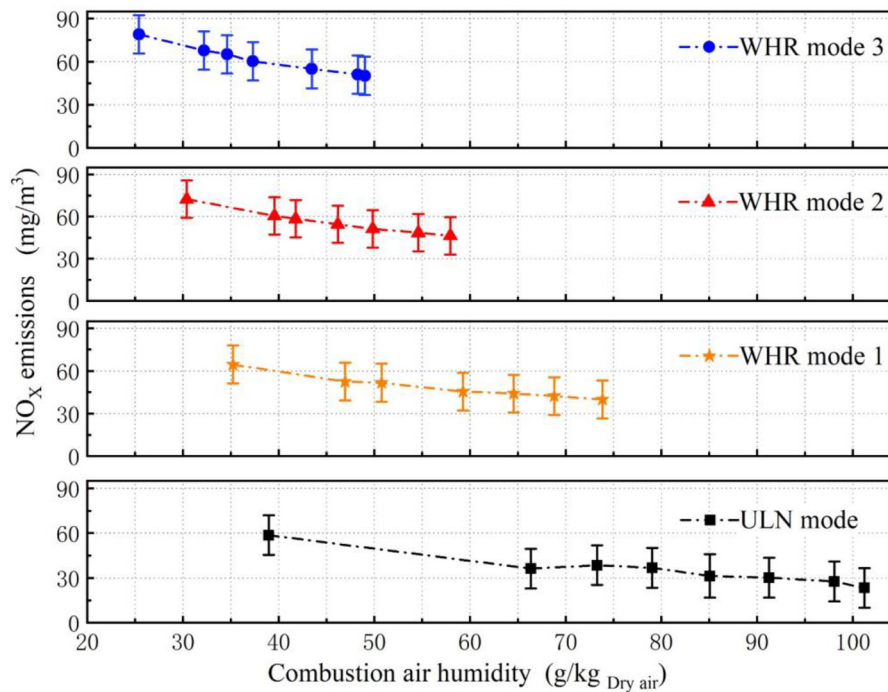


Figure 12. Effect of air humidity on NO_x emissions.

Discussion

NO_x emission reduction mechanism of combustion air humidification technology

The formation mechanism of nitrogen oxides includes three types: thermal, fast, and fuel. The thermal nitrogen oxides mechanism as put forward by Yakov Borisovich Zel'dovich (1914 – 1987) [24] explains an atomic chain mechanism for nitrogen oxide formation at high temperature, i.e., 1500 °C through chemical reactions, as shown in Fig. 13. According to Fenimore [25], prompt-NO_x is the most important mechanism. Prompt-NO is generated by the reaction of nitrogen with hydrocarbon radicals and O₂. Skreiberg et al. [26] proposed that prompt-NO in a majority of combustion systems accounts for less than 5% of all NO. Lupianez et al. [27] demonstrated that Fuel-NO_x is formed by nitrogen oxides inherent in the fuel. The concentration of nitrogen in the natural gas supplied by the Beijing City natural gas pipeline is 0.52% [18]. Thus, the proportion of NO_x in the fuel was small, and thermal NO_x accounts for more than 90% of the total NO_x emissions [28].

Pourhoseini [29] injected a silver-water nanofluid into a natural gas flame and studied its impact on NO_x emissions. The mechanism of NO_x emission reduction by water spraying was clearly explained. The spray water in the combustion air evaporates and absorbs heat during combustion, decreasing the maximum temperature of the flame. Temperature is the

main factor affecting the formation of thermal NO_x, and after the combustion of air humidification, the maximum flame temperature decreases, and therefore, nitrogen oxide concentration decreases. Dissociation of water can improve the OH radical concentration. OH radicals catalyze the oxidation of CO to consume O atoms. Consequently, the concentration of O atoms in the flame reaction zone decreased, reducing the formation of nitrogen oxides. This is also the reason for the reduction in NO_x emissions. Pugh et al. [30] confirmed that humidification combustion could reduce NO_x emissions through these two aspects in experiments using different burners.

Relationship between factors that affect NO_x concentration

Experimental studies were conducted on variables, such as F_s, LGR, H_a, T_a, operation mode, and T_s. Fig. 14 shows the relationship analysis of the influencing factors. The flow of spray water affects the LGR of exchanger B and the temperature and humidity of the combustion air. Combustion air humidity affects the concentration of NO_x in the boiler exhaust gas. Different system operating modes affect the spray water temperature and thus the combustion air temperature. The combustion air temperature affects the humidity and concentration of nitrogen oxides in the boiler exhaust gas. Therefore, the key factor is combustion air humidity.

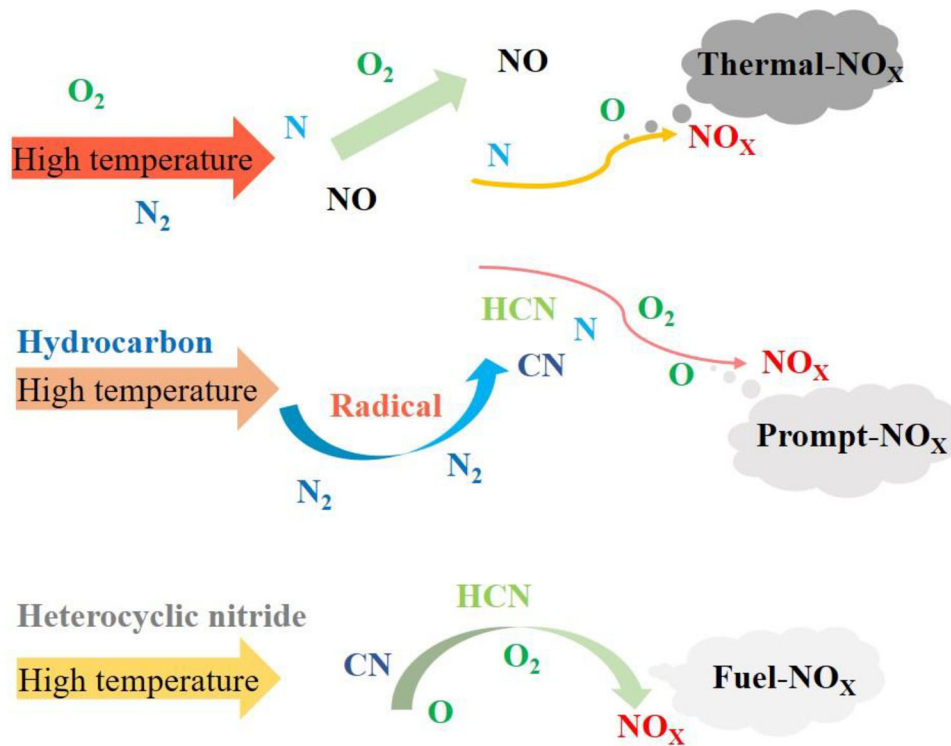


Figure 13. Formation mechanism of NO_x in gas boiler.

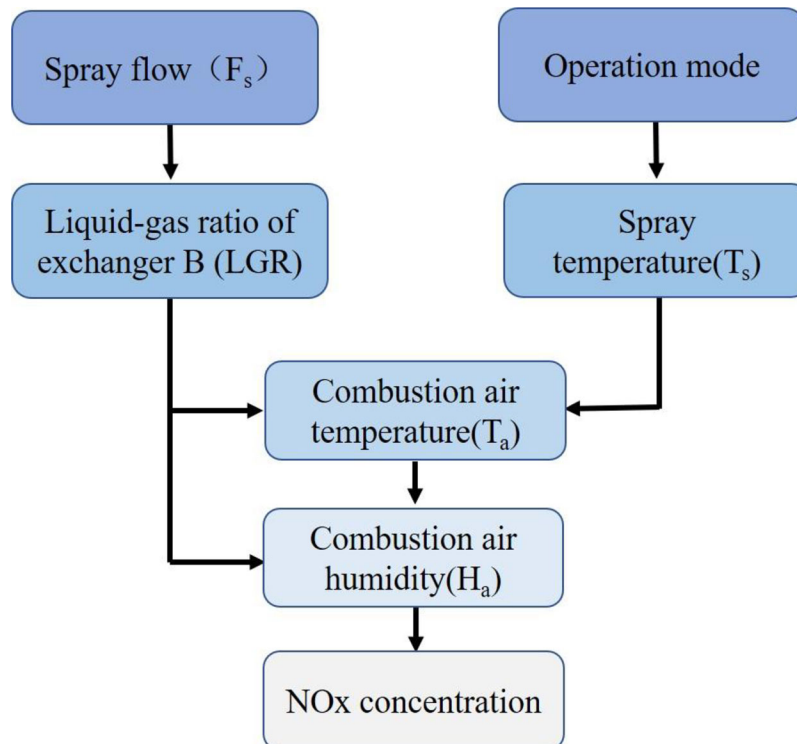


Figure 14. Relationship analysis of influencing factors.

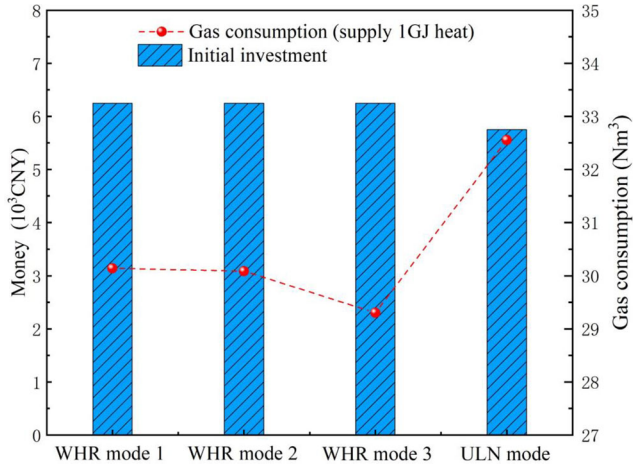
Economic feasibility analysis

In this section, we compare the economics of the different operating modes in terms of the initial investment and operating costs. The initial investment amounts for

the FGLNHR-CAH system are presented in Table 5. The ULN mode does not have a plate heat exchanger, thus, the initial investment is lower than that of the WHR operating mode, as shown in Fig. 15. The operating costs

Table 5. Initial investment of the FGLNHR-CAH system.

Items	Price (CNY)
Spray tower	3100
Water pump	1550
Water pipe, elbow	1000
Plate heat exchanger	500
Flue gas pipeline	60
Spray nozzle	40

**Figure 15.** Comparison of initial investment and gas consumption (maximum air humidity).

of the different modes differ because of their different total efficiencies. The amount of natural gas consumed by each mode to supply 1 GJ of heat was compared under the working conditions with the best NO_x emission reduction effect, as shown in Fig. 15. It can be observed that the natural gas consumption of the WHR mode is smaller than that of the ULN mode, which can also indicate that the WHR mode has lower operating costs.

$$B = \frac{Q_{out}}{Q_{net,ar} \times \eta_{Total}} \quad (16)$$

where B is the natural gas consumption, Nm³/h, Q_{out} is the output heat of the gas boiler (kW), $Q_{net,ar}$ is the low calorific value of natural gas, kJ/Nm³, and η_{Total} is the total system efficiency.

Therefore, the ULN mode is suitable for strict NO_x emission standards, but its operating costs are higher. The WHR mode NO_x emission reduction effect is not as good as that of the ULN mode, but this mode can recover waste heat and has a better energy-saving effect. It is worth noting that the initial investment of the two modes is low, which has the advantage of a low NO_x transformation in the gas boiler.

Conclusions

In this study, a flue gas with low NO_x emission and WHR system using combustion air humidification technology is proposed (FGLNHR-CAH). The effects

of high air humidity, WHR mode, and other factors on the NO_x emission reduction and efficiency of the system were studied. The emission reduction mechanism of this technology is also discussed. The technical economies of the two operating modes were evaluated. The primary results of this study are as follows:

1. Combustion air humidification can significantly reduce NO_x emissions but will affect the boiler efficiency slightly. However, the proposed WHR mode can effectively improve the total efficiency.
2. The ULN mode can obtain higher humidity combustion air, reducing NO_x emissions to 23.3 mg/m³. The boiler efficiency under these conditions was 86.9%.
3. The WHR mode can improve efficiency, but adversely affects the NO_x emission reduction effect. WHR mode 1 can reduce NO_x emission to 39.9 mg/m³ while increasing the total system efficiency to 93.8%.
4. Through an economic analysis, the ULN mode was found to be more suitable for strict emission standards. The WHR mode reduces the NO_x emission reduction rate; however, this mode can recover waste heat and has a better energy-saving effect. The FGLNHR-CAH system has the advantages of easy implementation, low cost, and good NO_x emission reduction and promotion.

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