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Experimental investigation on flue gas condensation heat recovery system integrated with heat pump and spray heat exchanger

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Abstract

To deeply recover the flue gas condensation heat, a flue gas condensation heat recovery system that combines a compression heat pump (FGCHR-HP) is proposed. An experimental bench of the FGCHR-HP system was established to explore the thermal properties of the system under variable operating conditions. The experimental results show that when the inlet water temperature of the heat pump condensing heat exchanger is 50 °C and the flow rate is 40 L/min, the optimal experimental conditions are achieved. Under this working condition, the heat efficiency is 13.8 %, and the exhaust gas temperature is 26.9 °C. At the same time, the flue gas moisture recovery is up to 6.5–7.0 kg/hour, which is better than other boilers. The payback period of the FGCHR-HP system is 3.4 years. The system has achieved significant energy-saving and water-saving effects, and has certain promotion and application prospects.

Keywords: Gas boiler, Heat pump, Spray tower, Flue gas heat recovery

Nomenclature

BHN backwater of the heating network

CNY Chinese Yuan

COP heat pump coefficient of performance

HP compression heat pump
 FGCHR-HP flue gas condensation heat recovery system with a compression heat pump
 HPCHE heat pump condensing heat exchanger
 FGWH Flue gas waste heat
 HX heat exchanger
 SHE spray heat exchanger
 B boiler natural gas consumption
 Cp constant pressure specific heat of spray water
 E1 instantaneous effective power input of HP, kW
 Qs waste heat recovery from flue gas, kW
 Qin input heat of gas boiler, kW
 Qr total heat output from the system, kW
 Qnet,ar minimum calorific value of natural gas, kW
 Qout heat loss from flue gas, kW
 U instantaneous voltage of HP, V
 cos ϕ power factor, 0.9
 ρ_w density of water vapor in flue gas, kg/m³
 T_{dp} dew point temperature of flue gas, °C
 Fv flow rate of BHN, L/min
 I instantaneous current of HP, A
 m_r mass flow rate of BHN, kg/s
 m_s mass flow rate of spray water, kg/s
 m_{H₂O} water vapor produced by combustion (T₁ > T_{dp}) kg/Nm³_{dry gas}
 p_t investment payback period, years
 Pw the partial pressure of water vapor in flue gas, kPa
 Se electric price, CNY
 Ag natural gas prices, CNY/Nm³
 Sg,s Cost saving of natural gas, CNY
 B_c Natural gas savings, Nm³
 Ae Unit price of electricity, CNY/(kW·h)
 Si Initial investment, CNY
 T1 outlet water temperature of SHE, °C

T_2 inlet water temperature of SHE, °C

T_3 inlet water temperature of HPCHE, °C

T_4 outlet water temperature of HPCHE, °C

η_T total efficiency of the system

η_r waste heat recovery efficiency

η_r waste heat recovery efficiency

η_o original boiler efficiency

1. Introduction

The prevailing energy crisis poses significant challenges to societal advancement and the maintenance of living standards [1], [2]. Empirical data suggests that a substantial 60 % of greenhouse gas emissions are attributable to energy consumption [3]. Consequently, endeavors to curtail energy use and enhance energy efficiency are pivotal for both economic growth and broader societal progression [4], [5]. Notwithstanding the escalating emphasis on renewable energy sources, fossil fuels remain the primary energy bedrock for the majority of nations. Recognized for its relative environmental benignity, natural gas is pivotal in boiler heating systems, accounting for over half of the energy input in gas boilers [6]. According to statistics, during the 2021–2022 heating season, in the urban areas of Beijing, gas heating covered an area of 633 million square meters, accounting for 68.88 % of the total heating area [7]. Gas boilers are gradually replacing coal-fired boilers. The temperature of flue gas produced by conventional gas boilers is about 200 °C, and the efficiency is about 90 % [8]. Exhaust flue gas contains a large amount of water vapor, with latent heat of gasification [9], [10]. According to statistics, the amount of water vapor carried in the flue gas emitted by our country is as high as 1.01 billion tons per year [11]. If the flue gas temperature drops from 180 °C to 35 ~ 40 °C, the thermal efficiency of the gas boiler can be increased by 13.9 %~15.1 % [12], and a large amount of water resources can be recovered. Therefore, the waste heat recovery of flue gas is an important means to protect environment and improve energy efficiency.

Early methodologies for flue gas heat recovery employed air preheaters and economizers to precondition the inlet air and recirculate the boiler feedwater [13]. Due to the inherently low specific heat capacity of air, only a fraction of the available sensible heat can be harnessed through the thermal exchange between air and flue gas. The recirculated boiler feedwater exhibits a relatively elevated temperature. Consequently, during the thermal transfer process, the requisite heat exchanger (HX) surface area becomes extensive, yet the actual heat transferred remains limited. Notably, residual sensible heat and latent heat of vaporization persist in the exhaust gas. Based on established heat transfer paradigms, condensing boilers can be categorized into indirect and direct thermal exchange mechanisms [14]. Hwang et al. [15] proposed a titanium HX which can effectively prevent pipeline corrosion for recovering latent heat of gas water heaters, and the thermal efficiency is increased to 93 %. Chen et al. [16] proposed a non-contact heat recovery system for gas boiler flue gas-supply air deep heat recovery method. Multi-stage HX mode is used for the flue gas by spraying water during the air supply process to absorb flue gas waste heat. The research can reduce flue gas temperature to 25 °C and increase the boiler efficiency to 103.4 %. As the research into flue gas waste heat recovery technology advances, the method for condensing flue gas waste heat recovery has been developed, building upon the initial waste heat recovery methods. This includes heat exchanger flue gas waste heat recovery [17], heat pump flue gas waste heat

recovery [18], and other waste heat recovery technologies [19]. Among these, indirect heat exchangers can usually recover the sensible heat of the flue gas [20], and the current research on membrane heat exchangers is not yet applicable on a large scale [21]. Direct heat exchangers, when using a lower temperature cold source as a spray heat exchange medium, can more thoroughly recover flue gas waste heat. The dew point temperature of natural gas flue gas is generally around 55 °C [22]. When performing deep condensing waste heat recovery, the temperature of the heat exchange water needed for spray heat exchange should be about 30 °C. The conventional practice is to use return water from the heating network as the spray medium. However, due to the relatively high temperature of this return water, its effectiveness in direct heat exchange with flue gas is reduced. Currently, the properties of heat pumps are often utilized to address the issue of high return water temperatures. Li et al. [23] established a flue gas–water direct heat exchange mathematical model and obtained a numerical solution for the temperature distribution. The results show that the heat exchange factors were affected by heat exchanger height, spray water atomization particle size, and water vapor ratio. Min [24] established a new experimental setup for flue gas heat and moisture recovery performance based on falling film spray technology, and systematically investigated the effects of water-to-air ratio and inlet air temperature on the heat transfer effect. The results showed that increasing the water-to-air ratio or decreasing the inlet air temperature could improve the heat transfer efficiency.

To reduce flue gas temperature of gas boilers, heat pumps (HP) are used to provide a low-temperature cold sources. Jouhara [25] et al. concluded that by recovering waste heat emitted to the environment and upgrading its quality through heat pumps, useful heat can be generated and used directly in the process to reduce energy intake and improve the overall efficiency of the system. The HP system mainly includes a compression heat pump (CHP) that consumes electricity and an absorption heat pump (AHP) driven by other heat energy [26]. Chen et al. [27] introduced a flue gas condensing heat exchangers combined with a CHP to recover waste heat. The working temperature of the cooling medium that heat exchange with flue gas is 25 °C ~ 35 °C, which is much lower than the backwater of heating network (BHN) temperature. The flue gas heat is transferred to the BHN at the condensing heat exchanger. The proposed system has a simple structure, but requires large investment and high energy consumption. Blarke and Dotzauer [28] proposed a flue gas waste heat recovery (FGWH) system that combines CHP and cogeneration. The plant fuel efficiency of this system increased from 88.9 % to 95.5 %. Due to the driving heat source energy can be provided by the boiler itself, absorption heat pumps are often used in large gas boilers [29]. Papers [30], [31], [32] used AHP recover FGWH to improve boiler thermal efficiency. Xu et al. [33] proposed a two-stage AHP system with two evaporation processes arranged in series, the heat pump coefficient of performance (COP) can reach 1.77. Zhang et al. [34] used an open absorption heat pump (OAHP) and flash vaporization system to recover waste heat in the coal-fired flue gas after desulfurization. Compared to the original system, the OAHP system COP is increased by 0.5 %~2.2 %. Papers [14], [29], [35], [36] also applied an open-cycle absorption heat pump to recover FGWH, which improves the boiler thermal efficiency and provides a reference for practical applications under variable operating conditions. At present, the OAHP system still has problems such as solution pollution and non-condensable gas affecting heat transfer, and the system is unstable [37]. The AHP system has high investment costs and large space requirements. Depending on the size of the boiler, the CHP system is suitable for 10 kW ~ 10 MW [38]. Compared to the AHP system, the CHP system has the advantages of simple systems and small space requirement and is suitable for recovering FGWH of small gas boilers.

In Beijing, there are numerous small and medium-sized gas heating boilers under 20 tons, including some small direct-supply gas hot water boilers that are directly connected to boilers

inside the boiler rooms. These smaller boilers are typically responsible for heating within their respective communities. The space in the boiler rooms is limited, and compared to large thermal power plants, they produce less flue gas, resulting in a smaller total amount of low-grade waste heat. Furthermore, the initial investment for absorption heat pumps is significant, with a long payback period [39]. This, coupled with the financial and technical limitations of boiler operators, leads to small and medium-sized gas boilers typically use compression heat pumps instead of absorption heat pumps. The heat pump gas boiler flue gas condensing waste heat recovery system addresses the issues of high thermal resistance and poor heat transfer performance in indirect heat exchangers and also resolves the problem of needing low-temperature spray water for spray-type flue gas waste heat recovery.

In order to deeply recover FGWH and improve the heat efficiency of gas boilers, a FGCHR-HP system is designed. The system consists of a spray heat exchanger (SHE) section and a CHP section. In the FGCHR-HP system, the HP provides a low-temperature cold source, and by spraying cooling water, it directly contacts the high-temperature flue gas in the SHE to exchange heat, reduces the exhaust gas temperature, and transfers FGWH to BHN. Compared with other systems, the direct heat exchange between the low-temperature spray water and high-temperature flue gas can reduce the heat transfer link and improve the system efficiency. An experimental system is built to study the heat recovery performance of the system under multi-factor and variable conditions. By analyzing various indicators such as waste heat recovery efficiency, heating efficiency, exhaust gas temperature, heat pump performance coefficient (COP), flue gas-spray water direct heat exchange efficiency, etc., the waste heat recovery effect of the system is explored. In addition, the energy saving, economic benefit and environmental effect of the system are also discussed.

2. Experimental system

2.1. System description

The schematic diagram and the measurement point distribution of the FGCHR-HP system are both shown in Fig. 1. The FGCHR-HP system is mainly composed of a spray tower flue gas heat recovery section, CHP section and gas boiler system. The former is designed as a flue gas-spray water direct heat exchange for recovering FGWH and the latter has subsections of evaporator (heat pump evaporator), condenser (heat pump condenser), compressor, Throttle valve, water pump and other auxiliary components.

- (1) The waste heat recovery section of the spray tower flue gas condensation system comprises a spray tower, a spray water pump, and a spray water tank. In the spray tower, the flue gas undergoes heat exchange with atomized spray water, thereby reducing the temperature of the flue gas. Furthermore, during the heat exchange process, a portion of the nitrogen oxides (NO_x) present in the flue gas dissolves in the spray water.

- (2) The CHP section is mainly composed of a compressor, a thermostatic expansion valve, and a plate heat exchanger forming the condenser and evaporator. The refrigerant of the HP exchanges heat with water in the evaporator and condenser to complete the transfer of recovered flue gas energy. The heat exchange process is as follows. In the evaporator part, the refrigerant evaporates absorbs the heat in the spray water. Then through the compressor, gaseous refrigerant condenses and releases heat in the condenser, and transfers the heat to the BHN. It can continuously transfer the heat of spray water to the boiler backwater, forming a complete heat transfer cycle with the spray system.

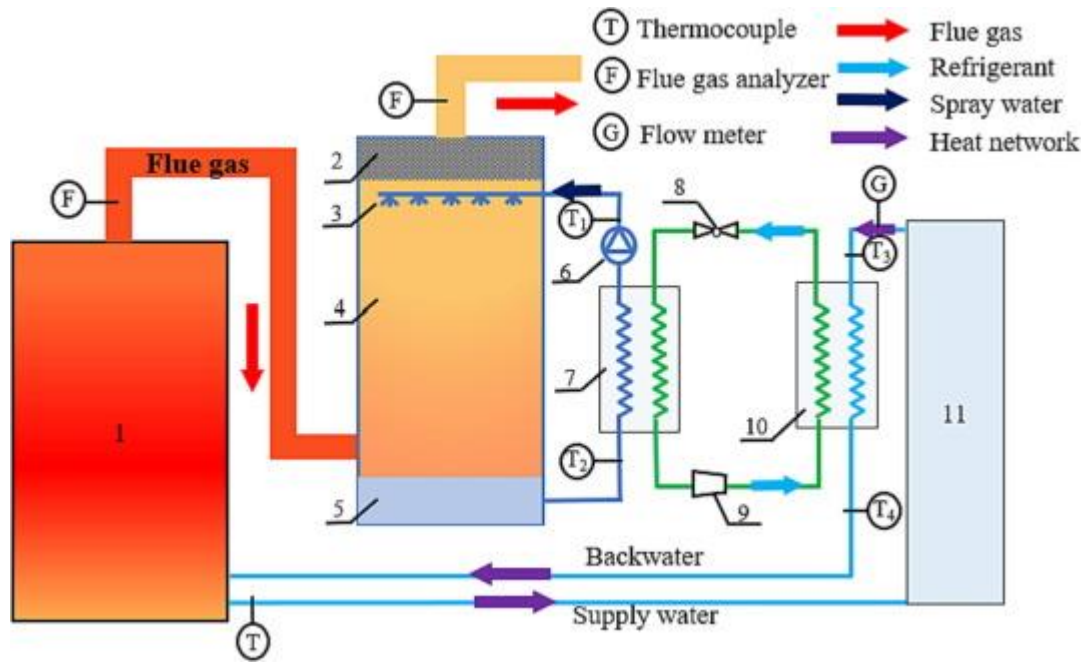


Fig. 1. Energy and mass flow rates diagram of the FGCHR-HP system (1. Gas boiler; 2. Droplet separator; 3. Spray nozzles; 4. Spray tower; 5. Spray water; 6. Spray pump; 7. Evaporator; 8. Throttle valve; 9. Compressor; 10. Condenser; 11. Heat user).

In accordance with this methodology, an experimental bench is constructed to evaluate the system's performance, as depicted in Fig. 2.



Fig. 2. The FGCHR-HP system experimental bench.

2.2. Experimental conditions and test methods

2.2.1. Experimental conditions

The nominal heat load of the boiler used in the experiment is 58 kW. This experiment mainly considers the influence of the flow rate and temperature of the BHN in the HPCHE on the FGCHR-HP system. The inlet water flow rate in the HPCHE is changed by the control valve on the pipeline. The inlet water temperature in the HPCHE is changed by adjusting the tank temperature. Other operating parameters of the gas boiler and design experimental conditions are shown in Table 1 and Table 2.

Table 1. Boiler operating parameters.

Parameters	Unit	Value
Flue gas temperature	°C	150–200
Natural gas consumption	Nm ³ /h	5.7
Excess air ratio	/	1.2
Boiler load	%	90
Flow rate of boiler water supply	L/min	30–40
Boiler heat capacity	kW	58

Table 2. Design experimental conditions.

Flow rate of BHN (L/min)	Inlet water temperature of HPCHE (°C)					
	30	40	42	44	46	48
35						
40						
Inlet water temperature of HPCHE (°C)		Flow rate of BHN (L/min)				
40	30	32	34	36	38	40
45						
50						

2.2.2. Test methods

The flue gas temperature is measured using a gas analyzer. The temperature of the BHN entering and leaving the heat pump condensing heat exchanger (HPCHE) is measured by T-type thermocouples. The flow rate of BHN is measured by float flowmeters. The temperature

and flow rate at the measurement point in the experimental system (see Fig. 1) are monitored by the above-mentioned sensors connected to the data collector. The main test instruments of type and accuracy the in Table 3.

Table 3. Experiment bench equipment and accuracy of main test instruments.

Item	Instrument	Model	Accuracy
Flue gas temperature	Flue gas analyzer	Testo340	±0.5 % (99–1200 °C)
temperature	Data collector	Agilent34972A	± 0. 004 %
Water temperature	Thermocouple	T-type	±0.3 °C
Flow rate of BHN	float flowmeters	LZM-25	±4%
HP instantaneous power	Rail type multifunction instrument	D52-2048	±1%

2.3. System parameters

Based on the actual conditions of the boiler used in the experiment, the design parameters of the spray heat exchanger and heat pump are shown in Table 4, Table 5. The size and height of the waste heat recovery device are determined by the target conditions. The spray tower of waste heat recovery device is designed to be composed of organic glass with a cylindrical diameter of 300 mm and a height of 1000 mm. The device consists of three sections. The bottom of the device is a spray collection section with a height of 350 mm. The middle of the device is a heat exchange section with a height of 550 mm. The top of the device is a defogging section with a height of 100 mm.

Table 4. Design parameters of flue gas status in spray tower.

Gas consumption	SHE Design inlet flue temperature	SHE Design inlet flue temperature	Design working condition Flue gas waste heat recovery
Nm ³ /h	°C	°C	kW
5.7	180	30	6.01

Table 5. Design parameters of each part of the heat pump system.

Evaporator design heat exchange	Condenser design heat exchange	Heat pump design COP	Electricity consumption
kW	kW	–	kW
6.01	8.01	4	2.00

The heat production required for this experiment is small, so a positive displacement compressor is used, with the specific parameters shown in Table 6.

Table 6. The technical parameters of the compressor.

model number	Power	Motor Type	exhaust volume	refrigerants	heating capacity	Working fluid mass flow rate	Maximum operating current
–	Horsepower	–	m ³ /hr	–	kW	g/s	A
ZW30KS-PFS	3	220 V single phase	7.1	R134a	10.1	43.5	17.2

For the evaporator and condenser, select the plate heat exchanger with better heat transfer performance among indirect heat exchangers. Use two KAORI stainless steel brazed heat exchangers with a heat transfer capacity of 14.06 kW each. The thermal expansion valve should be a Danfoss TN internally balanced expansion valve, suitable for temperatures ranging from $-40\text{ }^{\circ}\text{C}$ to $+10\text{ }^{\circ}\text{C}$.

The experiments were carried out using Beijing natural gas, and the specific composition and proportion are shown in the Table 7.

Table 7. the specific composition and proportion of natural gas.

Components	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₁₀	C ₅ H ₁₂	N ₂	CO ₂
Proportion/%	93.8	3.36	0.57	0.21	0.06	0.52	1.48

2.4. System evaluation model

To comprehensively evaluate the performance of the designed system, a series of evaluation models such as waste heat recovery efficiency, heating efficiency, COP, energy saving efficiency, environmental advantages and economic benefits are adopted. The performance evaluation model of the FGCHR-HP system is shown in Table 8.

Table 8. Energy, environment and economic models.

Type	Mathematical model	Definition
Energy	$Q_s = c_p m_s (T_2 - T_1)$	(1) Q_s kW Waste heat recovery from flue gas;
	$Q_s = Q_r - E_1$	(2) c_p kJ/(kg·K) Specific heat of spray water;
	$Q_r = c_p m_r (T_4 - T_3)$	(3) m_s kg/s Mass flow rate of spray water;
	$Q_{in} = B \cdot Q_{net,ar}$	(4) T_2 °C Inlet water temperature of SHE;
	$\eta_r = \frac{Q_r}{Q_{in}}$	(5) T_1 °C Outlet water temperature of SHE;
	$\eta_s = \frac{Q_s}{Q_{in}}$	(6) Q_r kW Total heat output from the system;
	$E_1 = \frac{U \cdot I \cdot \cos\phi}{1000}$	(7) m_r kg/s Mass flow rate of BHN;
	$COP = \frac{Q_r}{E_1}$	(8) T_4 °C Outlet water temperature of HPCHE;
	$COP_s = \frac{Q_r}{E_1 + E_2}$	(9) T_3 °C Inlet water temperature of HPCHE;
	$\eta_T = \eta_r + \eta_0$	(10) Q_{in} kW Heat input of gas boiler;
	B Nm ³ Natural gas consumption;	
	$Q_{net,ar}$ kJ/(kg·K) Minimum calorific value of natural gas;	
	η_r % Waste heat recovery efficiency;	
	η_s % Heating efficiency of the system;	
	E_1 kW Instantaneous effective input power of HP;	
	U V Instantaneous voltage of HP;	
	I A Instantaneous current of HP;	
	$\cos\phi$ power factor, 0.9;	
	COP Heat pump performance coefficient;	
	COP_s System performance coefficient;	
	η_0 % Original boiler efficiency;	
	η_T % Total efficiency of the system;	

Environment	$m_{H_2O} = \frac{V_{H_2O} \cdot P_0}{P_w} \rho_w$	(11)	m_{H_2O}	Kg	Water vapor content of combustion ($t_{s2} > t_{dp}$);	
	$\eta_2 = 1 - \frac{T_{s2} - T_3}{T_{s1} - T_1}$	(12)	P_w	kPa	Partial pressure of water vapor in flue gas;	
			ρ_w	kg/m ³	Density of water vapor in flue gas;	
			V_{H_2O}	m ³	Volume of water vapor in flue gas;	
			P_0	kPa	Pressure under standard condition;	
			T_{s2}	°C	Outlet flue gas temperature of spray tower;	
			T_{s1}	°C	Inlet flue gas temperature of spray tower;	
			η_2	%	Flue gas-spray water heat exchange efficiency;	
	Economic	$S_{g,s} = B_c \cdot A_g$	(13)	$S_{g,s}$	CNY	Cost saving of natural gas;
		$S_e = Q_e \cdot A_e$	(14)	B_c	Nm ³	Natural gas savings
$P_t = \frac{S_i}{S_{g,s} - S_e}$		(15)	A_g	CNY/Nm ³	Unit price of natural gas;	
			S_e	CNY	Electric price;	
			Q_e	kWh	Electricity consumption;	
			A_e	CNY/kWh	Unit price of electricity;	
			P_t	Year	Investment payback period;	
			S_i	CNY	Initial investment;	

3. Results

The boiler operates at 90 % load, 5.13Nm³/h gas consumption, and 30 ~ 40 L/min flow rate of BHN. A series of experimental measurements were carried out on the designed system to evaluate the FGCHR-HP system in terms of recovery efficiency, heating efficiency and HP performance, respectively.

3.1. Analysis of waste heat recovery efficiency

The FGCHR-HP system is analyzed by justifying the heat recovery efficiency (η_r) and heating efficiency (η_s). In practical projects, the heat obtained by the BHN is influenced by the inlet

water temperature and flow rate at the HPCHE. In this section, the influences of the two key parameters upon the system performance are evaluated.

Fig. 3 depicts the variation trend of waste heat recovery efficiency (η_r) with backwater temperature under three backwater flow conditions. At the same inlet water temperature of the HPCHE, the efficiency (η_r) increases with the increase of the flow rate of the BHN. This is the same as the change trend of the heat efficiency (η_s) of the system under the same experimental conditions. Under a given inlet water temperature of the HPCHE, increasing the flow rate can significantly improve the heat efficiency. According to the experiment, when the flow rate of BHN is 40 L/min and the inlet water temperature of HPCHE is 50 °C, the system waste heat recovery amount is 7.1 kW, the efficiency (η_r) is 10.2 %, and the heating efficiency (η_s) is 13.8 %. Since the system is merely a validation system and has not been optimized for matching, there are instances where the temperatures at the hot end and the cold end do not match. Therefore, under the same return water flow rate, the temperature curve does not strictly follow an increasing or decreasing trend.

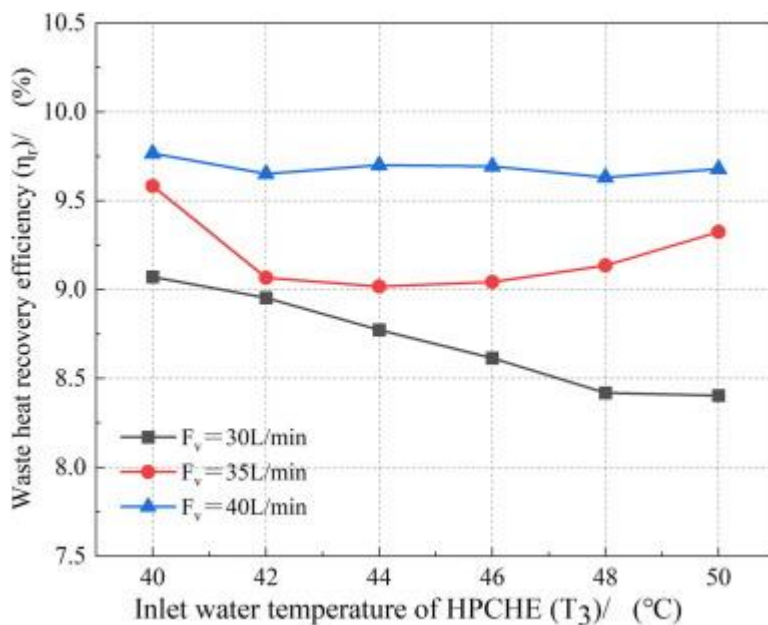


Fig. 3. Influence of the flow rate of the BHN on waste heat recovery efficiency.

Fig. 4 also depicts the variation trend of heating efficiency (η_s) with flow rate of the BHN under three inlet water temperature of the HPCHE conditions. The results suggest that with the continuous increase of water temperature, the heating efficiency (η_s) shows different trends under different constant flow conditions. Compared with the three water temperature conditions, when the inlet water temperature is 45 °C, it shows the best waste heat recovery performance. As the HPCHE inlet water temperature varies, the maximum fluctuation value of waste heat recovery is only 6.7 % of the input gas heat. The analysis found that the heat gain of the BHN from the HPCHE comes from two aspects, one is the heat transfer of spraying water in the evaporation section of the HP, and the other is the energy consumption of the HP operation. The lower spray water temperature has ensured the deep recover FGWH, but with the increase of the inlet water temperature, it will affect the COP, thereby affecting the heat

gain of the BHN at the HPCHE. Therefore, when increasing the flow rate of the BHN, the appropriate inlet water temperature of the HPCHE (T_3) to improve the heat efficiency.

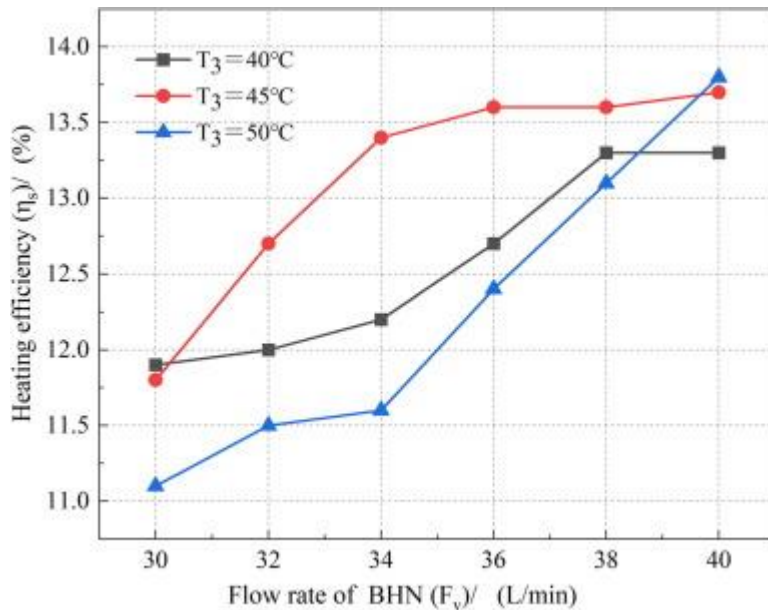
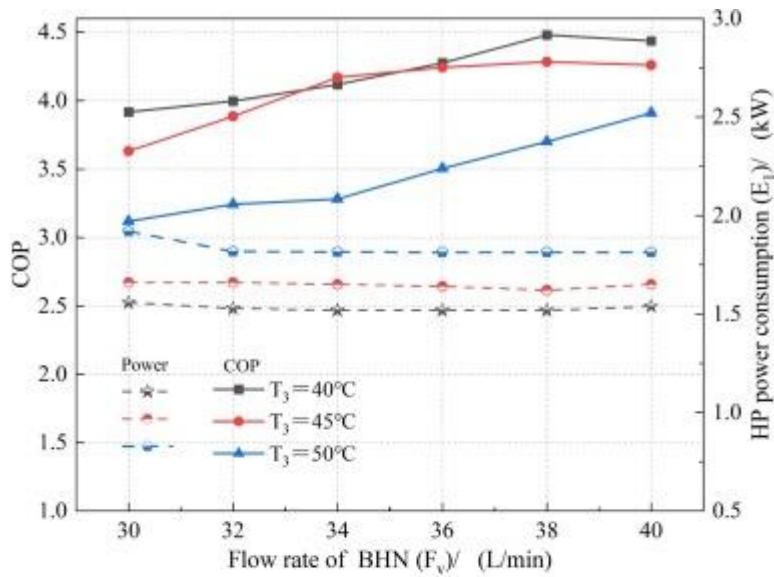


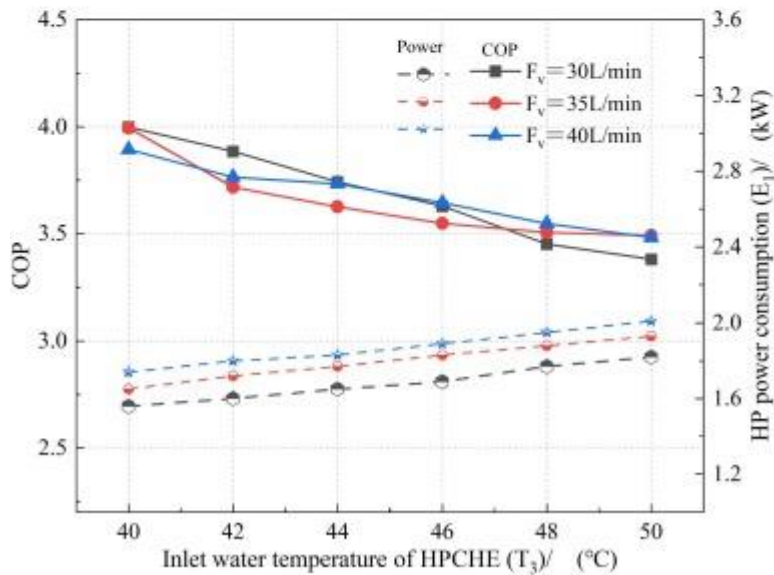
Fig. 4. Influence of the temperature and flow rate of the BHN on heating efficiency.

3.2. Analysis of heat pump COP effect of the system

COP is used to examine the performance of HP section for the FGCHR-HP system. Effects of inlet water temperature and flow rate of BHN on COP are explored. The COP is the ratio of the heat gained by the BHN to the power consumption of the HP operation. Fig. 5 depicts the experimentally measured COP values under various operating conditions. The results show that when the inlet water flow rate of BHN is constant, the COP performance decreases with the increase of the water temperature of the HPCHE. Furthermore, it also increases the power consumption of the HP system. In other words, when the load of the heat user increases, the temperature of the inlet water of the HPCHE decreases, and the temperature difference between the HP and the circulating working fluid of the HP increases. This improves the heat transfer effect of the HP on the BHN, and increases the COP. When the flow rate of the BHN (F_v) is 35 L/min, the inlet water temperature of the HPCHE decreases from 50 °C to 40 °C, and the COP increases from 3.49 to 3.99. Increasing the flow rate of the BHN at the HPCHE can also improve the COP. This is due to the increase flow rate of the BHN, which increase in the disturbance of the heat exchanger, thereby improving the heat exchange performance. When the inlet water temperature of the HPCHE is 38 °C and the flow rate of the BHN is 40 L/min, the COP can reach 4.48.



(a)



(b)

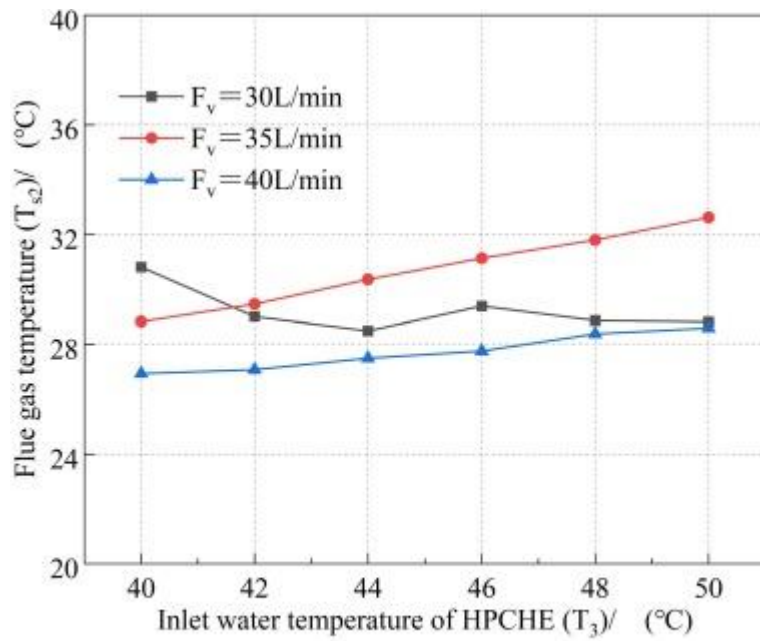
Fig. 5. Influence of the temperature and flow rate of the BHN on the COP.

With the increase of the inlet water temperature of the HPCHE or the decrease of the flow rate of the BHN, the COP value shows downward trend. That is to say, to recover the same waste heat, the HP needs more energy consumption. Different from the comprehensive effect of temperature on the COP under the condition of variable flow rate, the improvement of the COP is based on the fact that the energy consumption is basically unchanged. This means that the heat pump recovers more waste heat for the same drive power consumption.

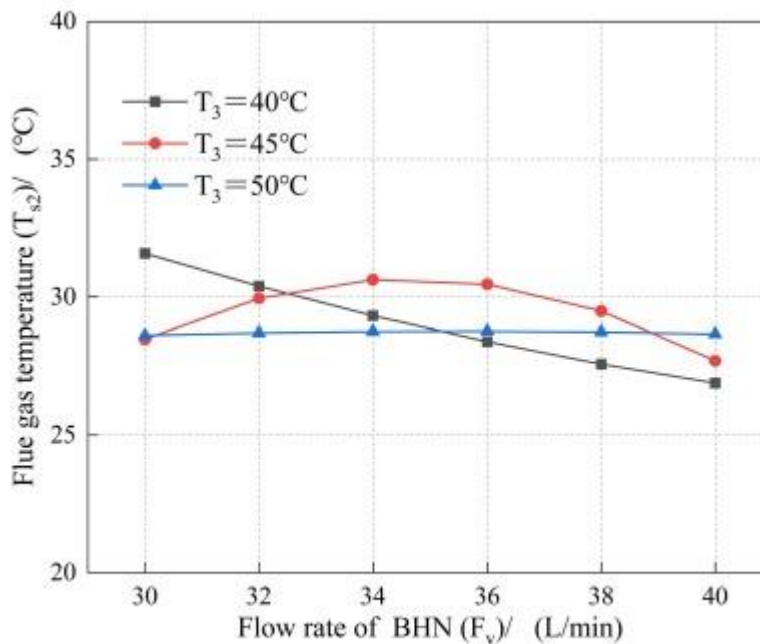
3.3. Analysis of exhaust flue gas temperature effect of the system

As shown in Fig. 6, the experiment study the influence of the inlet water temperature of the HPCHE and flow rate of BHN on the exhaust gas. The exhaust gas temperature of the system is around 30 °C. Increasing the water flow of the BHN or lowering the water temperature of

the HPCHE can reduce the exhaust gas temperature and achieve the deep recover FGWH. When the water temperature of the HPCHE is 40 °C and the flow rate of the BHN is 40 L/min, the exhaust gas temperature of the system can be reduced to 26.9 °C, which can greatly reduce the exhaust gas temperature. This suggests that the spray water in the spray tower can deeply absorb the FGWH, deeply reduce the heat loss of the flue gas, and greatly decrease the boiler flue gas temperature.



(a)



(b)

Fig. 6. Influence of the temperature and flow rate of BHN on the exhaust flue gas temperature.

4. Discussion

To further explain the rationality of the FGCHR-HP system, this section presents a comparative analysis of the system from the aspects of energy, environmental and economic. Finally, the influence of improving the COP on the recovery efficiency of the system is discussed and analyzed. The operating condition of FGCHR-HP system is selected for analysis when the temperature of the BHN at the HPCHE is 45.0 °C and the flow rate of the BHN is 40.0 L/min.

4.1. Energy analysis

Energy saving is the most fundamental purpose of this system. The evaluation models in Table 3 are used to compare and analyze the energy-saving effects of the system. The total efficiency and gas consumption of different boiler systems when 1 GJ heat is generated are compared in Fig. 7. It can be found that the FGCHR-HP system can save 3.9Nm³ of gas consumption compared to a conventional boiler, while increasing the system efficiency to 103.8%. At the same time, the CO₂ emission of the FGCHR-HP system is reduced by 7.71 kg compared with the conventional boiler, which is conducive to environmental protection and the trend of national requirements for energy conservation and emission reduction.

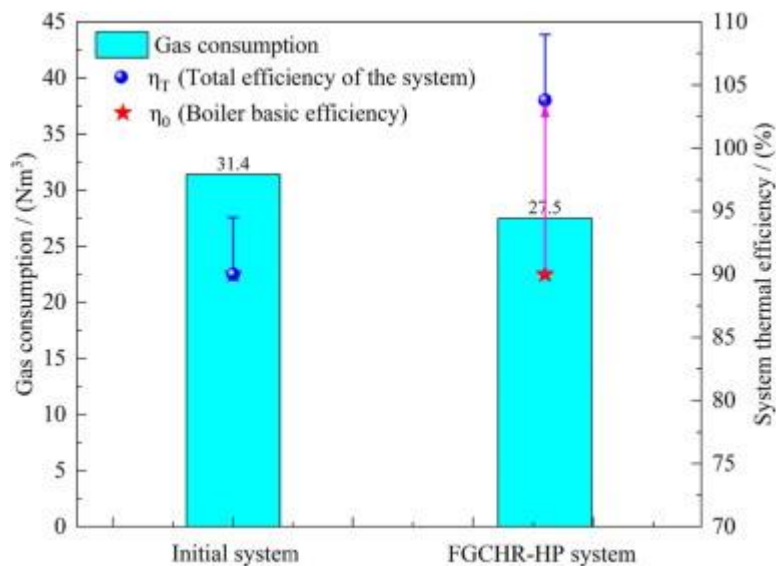


Fig. 7. Gas consumption and system heat efficiency of different boilers.

Fig. 8 illustrate the system energy flow in the view of energy balance analysis. The analysis is carried out under the conditions that the temperature of the BHN at the HPCHE is 50 °C and the flow rate is 40 L/min. The percentage of heat in the energy flow diagram is calculated according to a minimum calorific value of natural gas. The final heat transfer direction of the FGCHR-HP system is the FGWH to the BHN. After the natural gas is burned in the furnace, 90% of the heat of the boiler is supplied to the heating network. In stable operations, the flow rate of the boiler flue gas is basically unchanged, and the heat content of the flue gas can be achieved as 20% by combining the enthalpy value of the flue gas. Under these conditions, the COP of the heat pump is about 3.83, so that 13.8% of the FGWH can be recovered when the input power to the HP is 3.6%. According to the heat balance, the total flue gas and heat dissipation loss of the system is 9.8%. It is worth pointing out that the exhaust temperature of

this system is low. Therefore, the emission loss (Q_{out}) is mainly the thermal dissipation of the system. If the FGCHR-HP system is optimized to reduce heat loss during the conveying process, the system efficiency can be further improved.

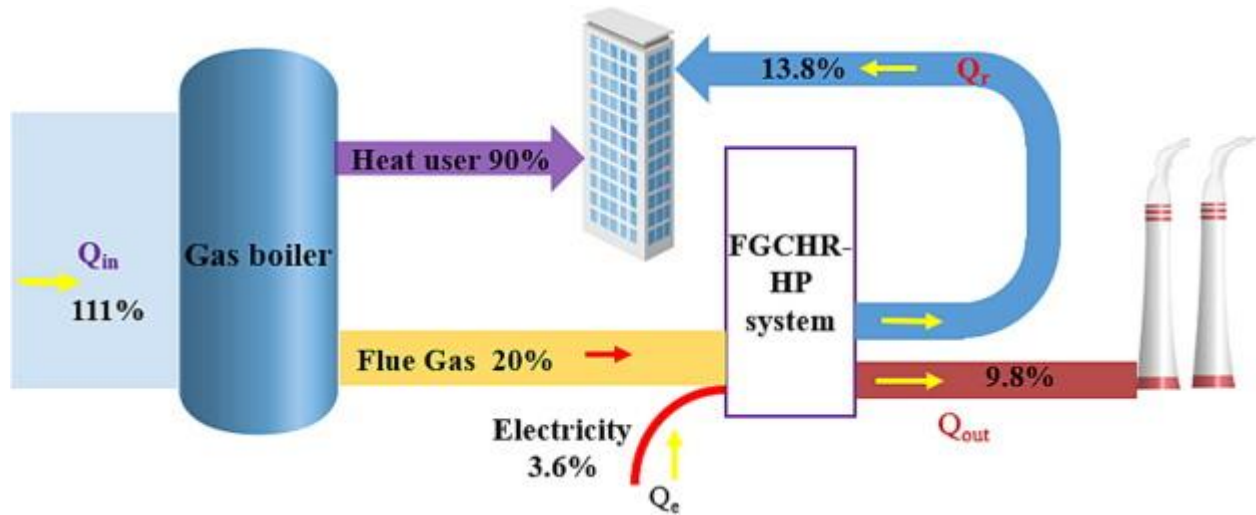


Fig. 8. Energy balance-based flow chart for the FGCHR-HP system.

4.2. Environmental analysis

4.2.1. Carbon emission analysis

Electric energy as secondary energy needs to be converted from primary energy. If this conversion efficiency is considered, the system requires more energy to recover 13.8 % of the flue gas waste heat. In this situation, according to the conversion relationship, 13.8 % of the residual heat of flue gas and the electric energy consumed are converted into standard coal. Fig. 9 shows that the standard coal saved by recovering 13.8 % of the FGWH and the standard coal generated by the electricity consumed in the process are 61380 kg/Year and 14411 kg/Year respectively. At the same time, the CO₂ produced is 24626 kg/Year and 5782 kg/Year respectively.

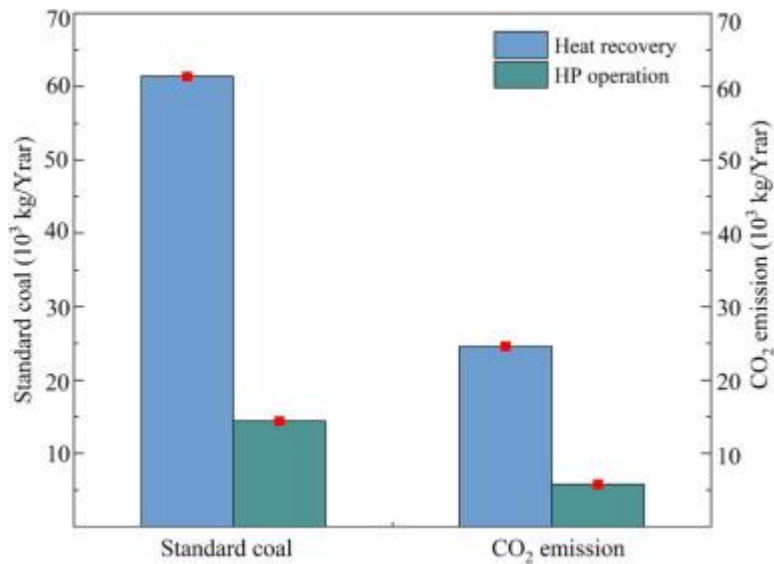


Fig. 9. CO₂ emissions and coal consumption for two systems per GJ heat.

4.2.2. Analysis of flue gas-spray water heat transfer efficiency

The flue gas and atomizing spray water are fully heat exchanged in the spray tower, and the flue gas is discharged after condensing and cooling. Fig. 10 shows the heat transfer efficiency is mostly above 97 %, and with the increase of the temperature(T_3) and flow rate (F_v), the heat exchange efficiency shows an increasing trend. The spray tower has less heat dissipation in the heat recovery process, and the atomizing spray water can fully absorb the energy of the enthalpy differential flue gas in the spray tower. The flue gas and spray water can fully exchange heat and moisture, greatly reducing the amount of water vapor in the exhaust gas of boiler, and can largely solve the “white smoke” phenomenon.

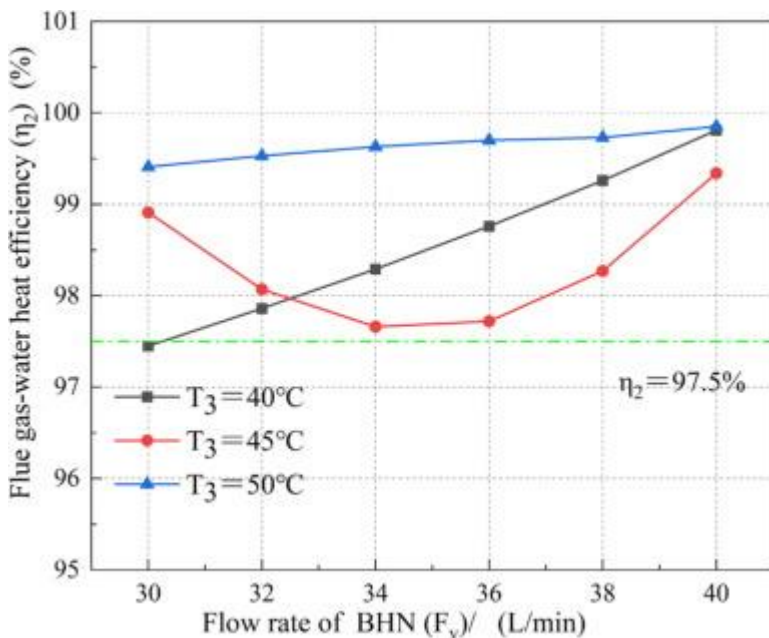
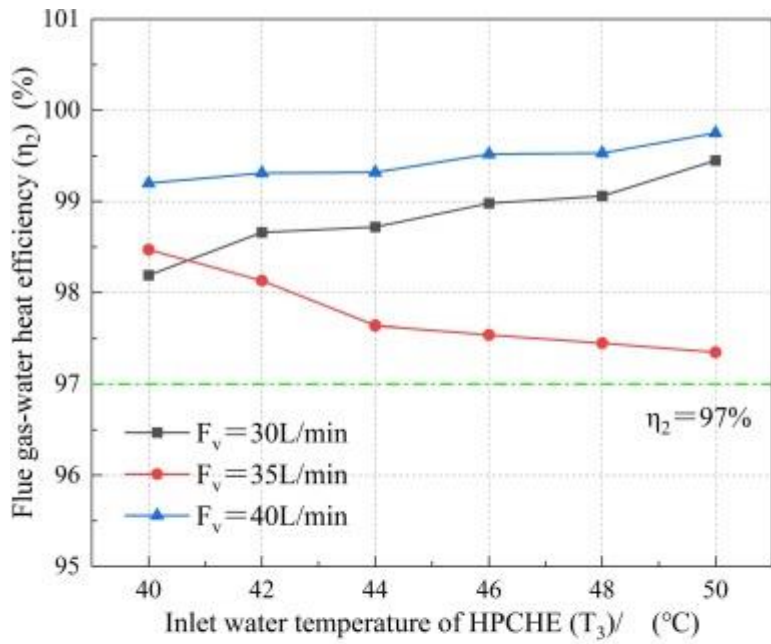


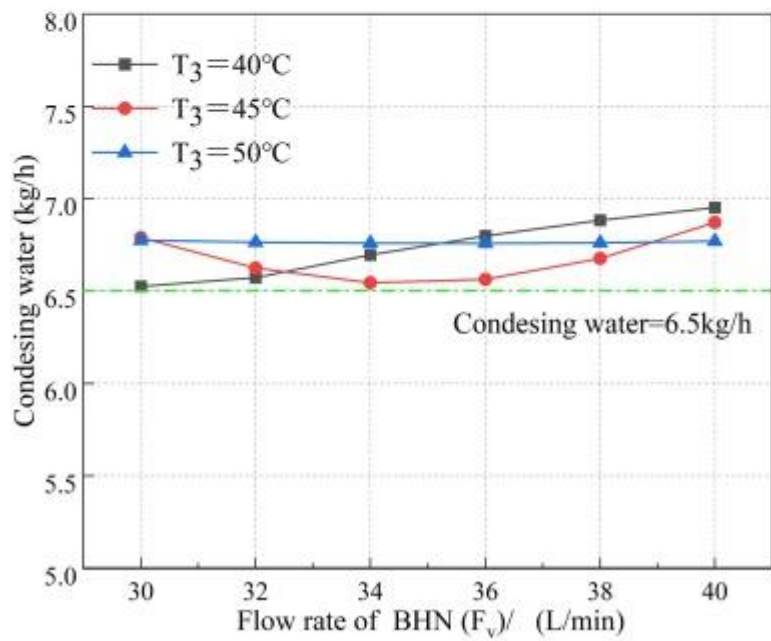
Fig. 10. Flue gas-spray water heat efficiency of FGCHE at different inlet water flow rates and temperatures.

4.2.3. Analysis of the influence of the system water recovery rate

Due to the reduction of the exhaust gas temperature, the water vapor in the flue gas condenses and falls into the water storage tray at the bottom. After treatment, the condensed water in the water storage tray can be used as a make-up water system for the boiler and the heat network. It can be seen from Fig. 11, Fig. 12 that the flue gas condensation amount of water vapor is 6.5 ~ 7 kg/h, and the water vapor content in the exhaust gas is reduced by more than 75 %. When the temperature of the BHN at the HPCHE is 40 °C and the flow rate is 40 L/min, the highest water recovery rate can reach 81.2 %. The system can effectively reduce the moisture in the flue gas to a certain extent, and has a good water saving effect. If this 58 kW gas boiler is used for heating, after a heating period (4 months), 31.2 ~ 33.6 m³ of flue gas condensate can be recovered, saving a lot of water resources. Zhou et al.[40] tested the pH value of condensate water after spray cooling of natural gas flue gas. The experimental results indicated that the pH value of the condensate water is approximately 5, showing acidity. Therefore, the condensate water needs to undergo certain treatment before it can be further used as supplementary water for the thermal piping network.



(a)



(b)

Fig. 11. Influence of the flow rate of BHN on condensed water.

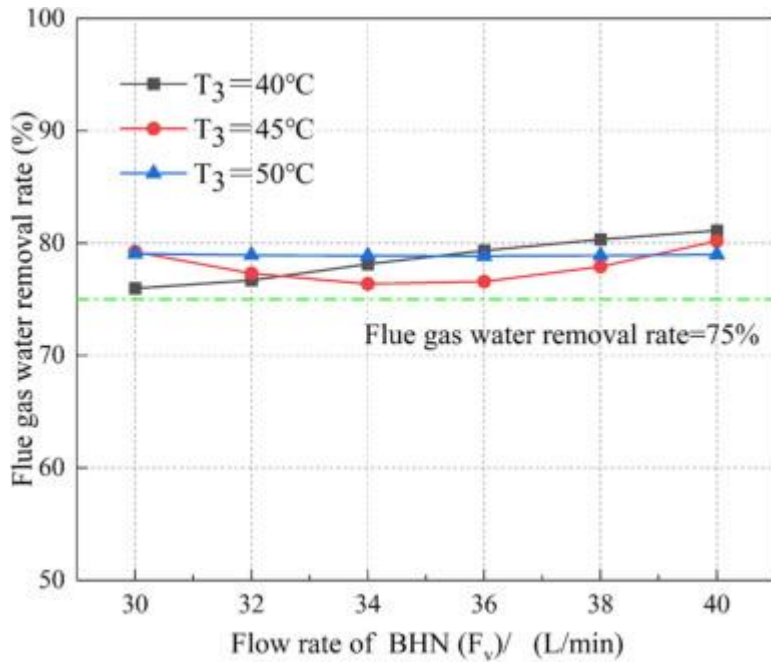


Fig. 12. Influence of the flow rate of BHN on the flue gas removal rate.

4.3. Economic analysis

The economy of the FGCHR-HP system can be evaluated by the payback period, which is calculated by Eq. (13), Eq. (14) and Eq. (15) in Table 7. The initial investment is the sum of the prices of all equipment and materials in the system. The initial investment of the FGCHR-HP system is shown in Table 9. Economic evaluation of FGCHR-HP system and conventional boiler system.

Table 9. Initial investment of the FGCHR-HP system.

Items	Price (CNY)
HP system (except power distribution)	4000
HP power distribution	900
Spray tower	1400
Spray pump	300
Other	200
Summation	6800

The FGCHR-HP system running cost is mainly composed of fuel cost and power consumption of the pump. Gas prices are based on non-resident gas prices for the winter of 2020 in Beijing. Electricity prices are based on non-resident sales prices in January 2021 in Beijing. Table 10 shows the relevant parameters for calculating the operating costs of the system. When the

flow rate (F_v) is 40 L/min and temperature (T_3) is 45 °C, the recover FGWH is 7.0 kW, and the power consumption of the HP is 1.65 kW. The payback period time for both boilers is shown in Fig. 13. Compared with the initial system, the operating cost of the FGCHR-HP system is reduced by 1701 yuan per year, and the system investment payback period is 3.4 years. The advantages of the FGCHR-HP system gradually emerged as the system running time increased.

Table 10. Parameters for operating cost analysis.

Heat recovery kW	Gas prices CNY/Nm ³	Operating power consumption kW	Electrovalence CNY/kW. h
7.028	2.78	1.65	0.7673

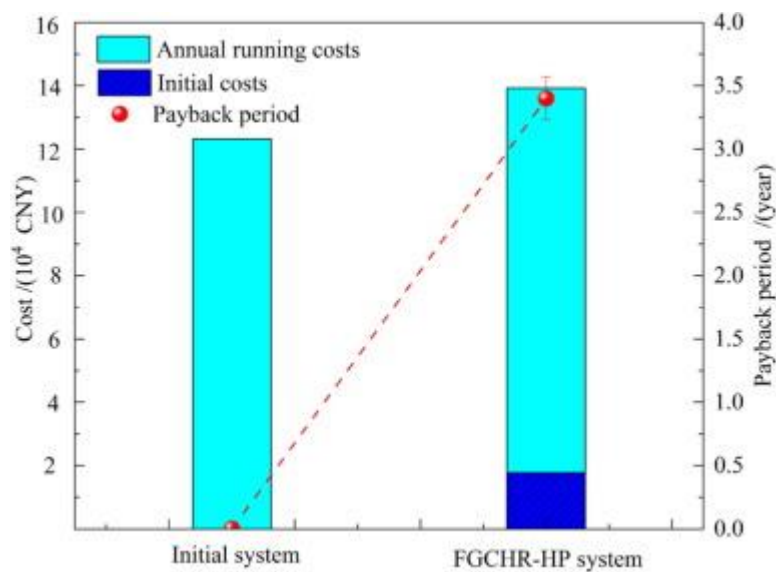


Fig. 13. Economic comparison diagram of two boiler systems.

4.4. Performance of the heat pump system analysis

The performance of the HP system is particularly important for the FGCHR-HP system. The HP performance difference directly affects the waste heat recovery capacity and energy consumption of the FGCHR-HP system. Based on experimental study, the influence of the COP on the FGCHR-HP system is analyzed. As seen in Fig. 14, when the flow rate (F_v) is 40 L/min and the temperature (T_3) varies, the heat efficiency (η_s) of the FGCHR-HP system increases significantly with the rise in COP. When the COP is increased by 30 %, that is, when the COP is increased to about 5, the heat efficiency (η_s) can be increased by 17.5 %. At this time, the comprehensive performance COP_s of the FGCHR-HP system is increased to 3.6. In the case of recovering the same waste heat, the energy consumption of the FGCHR-HP system is significantly reduced. As can be observed from Table 11, the system operating cost and investment payback period are greatly reduced. Therefore, improving the COP is more crucial for recovering flue gas waste heat in the FGCHR-HP system (see Table 12).

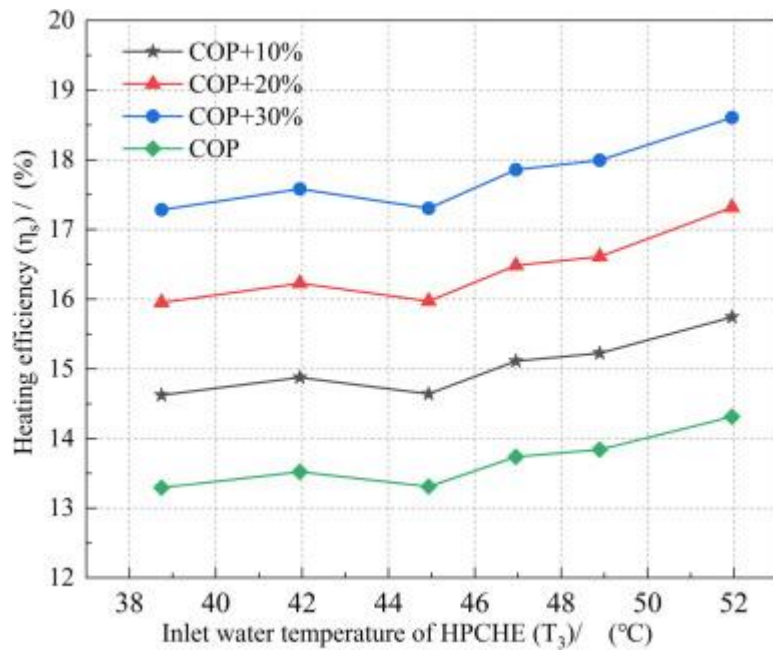


Fig. 14. Influence of COP on heating efficiency of the system.

Table 11. Operating Cost and Return Period of Waste Heat Recovery System.

Items	Unit	Initial system	FGCHR-HP system
Fuel saving	CNY/h	0	1.96
Initial investment	CNY	0	6800
Operating cost	CNY/Year	123,218	121,517
Payback period	Year	0	3.40

Table 12. Comparison of simulated and experimental values.

Parameters	SHE inlet flue gas temperature	SHE outlet flue gas temperature	Evaporator inlet water temperature	Evaporator outlet water temperature	Condenser inlet water temperature	Condenser outlet water temperature
unit	°C	°C	°C	°C	°C	°C
experimental value	151.7	30.8	28.3	13.1	40.0	42.9
simulated value	157.8	28.1	26.5	11.6	41.8	44.3

4.5. Sensitive analysis

Based on the experimental system process using Aspen Plus 9.0 to build the system model, using Gibbs reactor to simulate the boiler combustion process, the rest of the model parameters are set according to the parameters of the experimental system, the system model diagram is shown in Fig. 15.

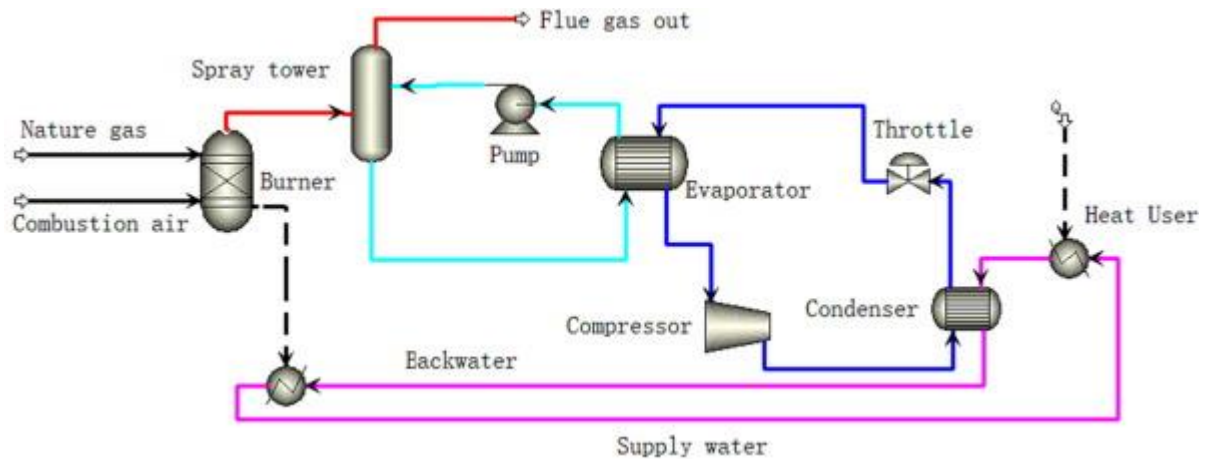


Fig. 15. Aspen Plus model diagram of the system.

Considering a water flow rate of 30 L/min at the condenser end of the heat pump, and an inlet water temperature of 40 °C, key parameters of the system were calculated and compared with experimental results. The discrepancy between the process simulation results and experimental outcomes is minimal, ensuring the accuracy of the thermal simulation calculations.

Fig. 16 shows the impact of natural gas prices on the system's payback period under different boiler loads. It can be observed that as the price of natural gas increases, the payback period for the system investment decreases. This is because, with a fixed amount of flue gas savings, an increase in natural gas prices means more capital is recuperated, thereby shortening the investment payback period. Additionally, as the operational load of the boiler increases, the system's payback period is further reduced.

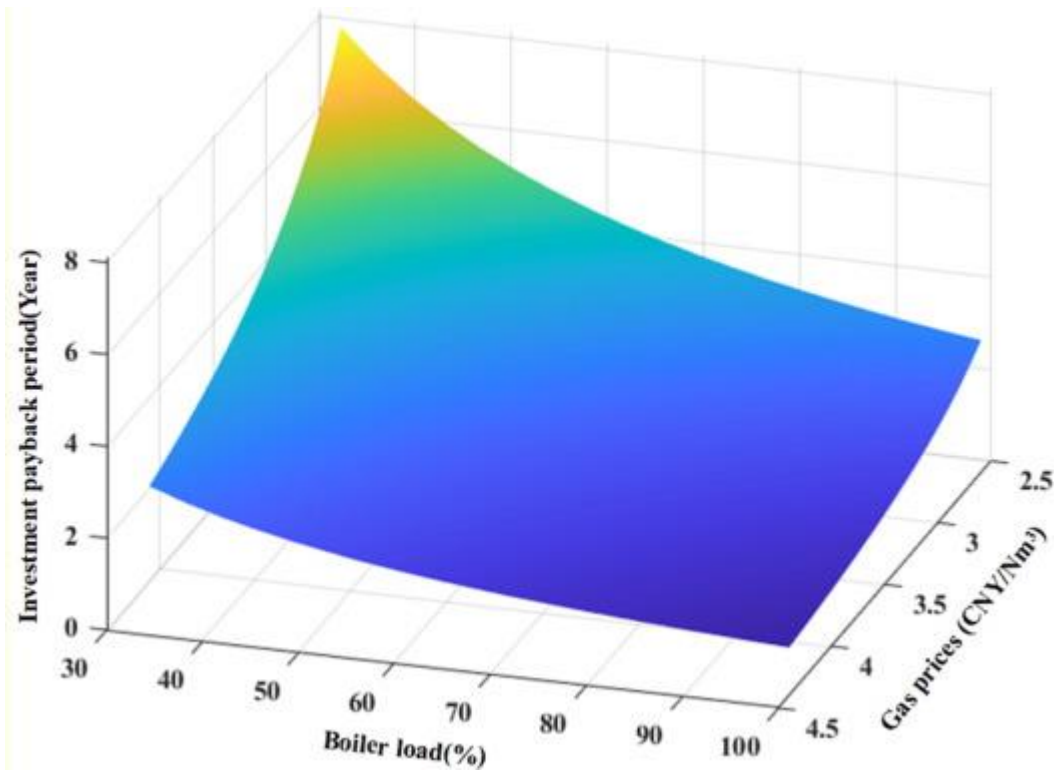


Fig. 16. Natural gas price sensitivity analysis.

Fig. 17 illustrates the impact of the metering heating price on the system's investment payback period under different boiler loads. It is evident that as the metering heating price increases, the payback period for the system investment correspondingly shortens. This is because, with a fixed amount of waste heat recovery by the system, an increase in the metering heating price implies an increase in the recuperated funds, which in turn leads to a reduction in the investment payback period.

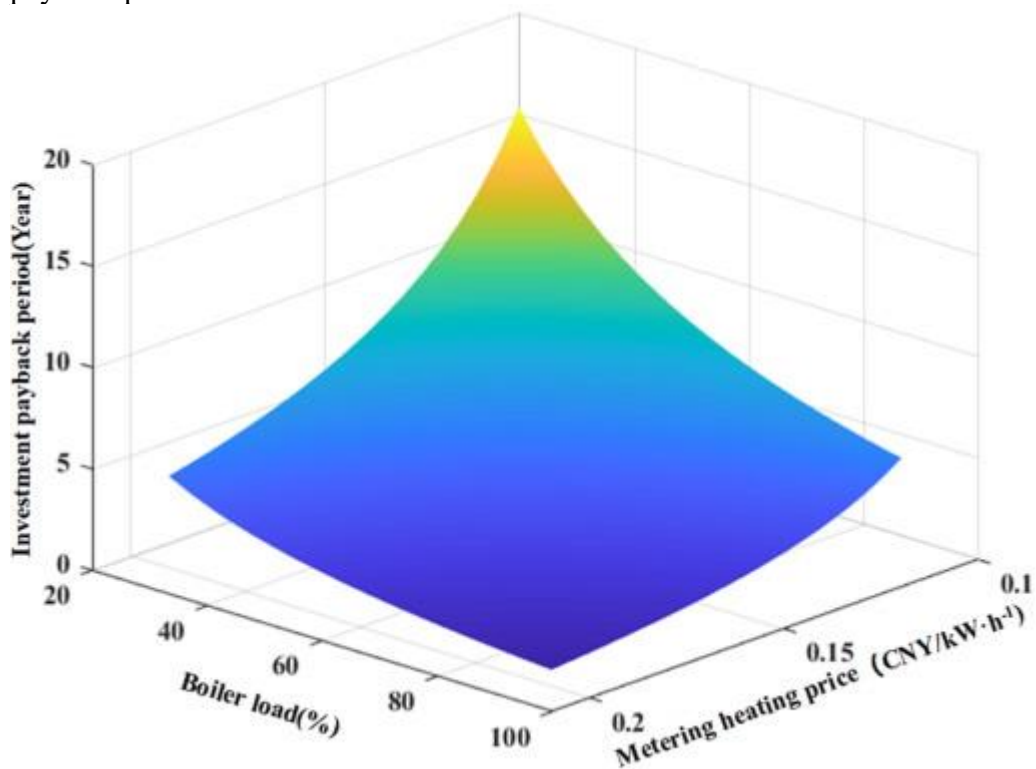


Fig. 17. Metering heating price sensitivity analysis.

5. Conclusion

This paper proposes a novel FGCHR-HP system, which uses a spray tower with higher heat exchange efficiency and a certain purification function to directly exchange heat to recover the FGWH. This system can solve the problem of low-temperature cold source required when spraying direct heat exchange to deeply recover flue gas waste heat. The main findings are set out below:

- (1)
The efficiency (η_s) increase with the increase of the flow rate (F_v). When the inlet water temperature (T_3) increases, the thermal efficiency (η_s) remains almost unchanged, and the overall performance COP_S of the FGCHR-HP system decreases. At this time, when the inlet water temperature (T_3) is 50 °C and the flow rate (F_v) is 40 L/min, the heat efficiency (η_s) can reach 13.8 %, and the waste heat recovery can reach 7.1 kW;
- (2)
Lowering the inlet water temperature (T_3) or increasing flow rate (F_v) can improve the performance of the HP. When the inlet water temperature (T_3) is 40 °C and the flow rate (F_v) is 38 L/min, the maximum COP is 4.48;
- (3)
Lowering the temperature (T_3) or increasing the flow rate (F_v) can reduce the exhaust gas temperature of gas boiler. When the inlet water temperature (T_3) is 40 °C and the flow rate (F_v) is 40 L/min, the exhaust gas temperature can be reduced to 26.9 °C;
- (4)
The heat exchange between the flue gas and the atomized spray water is fully carried out in the spray tower. The gas boiler FGWH can be deeply recovered. Flue gas-spray water direct heat exchange efficiency is over 97 %, and 75 % of the water vapor in the flue gas can be recovered. The condensation amount of water vapor in the flue gas is between 6.5 ~ 7 kg/h, which not only achieves the purification of flue gas, but also realizes the recovery effect of residual water;
- (5)
The FGCHR-HP system has a low initial investment and the energy-saving benefit is better with a payback period is 3.4 years. The FGCHR-HP system has good energy efficiency and economic benefits, and has high promotion value.

CRediT authorship contribution statement

Qunli Zhang: Methodology, Project administration. **Tao Liu:** Software, Writing – original draft. **Xuanrui Cheng:** Data curation. **Shuaifei Guo:** Validation. **Lin Zhang:** Formal analysis. **Xiaoshu Lü:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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