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The Design and Experimental Study of a Deep-Condensing Waste Heat Recovery System for Boiler Flue Gas Based on Baoneng Heating Plant

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Abstract: As China continues to adjust its energy structure in order to address energy security and environmental crises, changes in centralized heating technology and energy saving are gradually being promoted. Flue gas waste heat recovery from traditional gas boilers has the potential to play a significant role in the promotion of low-carbon heating, energy saving, and emission reduction. This study took the Beijing Baoneng Heating Plant as its research object. We designed a flue gas deep-condensation waste heat recovery system based on the combination of absorption heat pump technology and stepped waste heat recovery technology. We determined that 40 °C is the target temperature for flue gas: At this point, the condensate in the flue gas is precipitated by approximately 60%. This results in a 12.18% efficiency improvement in the boiler. Subsequently, experimentation demonstrated that the recovered flue gas heat was able to fulfill the heating requirements of the Baoneng plant and that it was able to enhance the heating capacity of the heat source plant by utilizing the flue gas waste heat without increasing energy consumption. This represents a mutually beneficial scenario for environmental and economic considerations.

Keywords: gas boiler; latent heat of flue gas; waste heat step recovery; absorption heat pump; modified polypropylene

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1. Introduction

In light of the mounting global energy deficit and environmental degradation, countries across the globe are continually adapting their energy portfolios to address the environmental crisis. As a source of energy with a lower carbon content, natural gas has demonstrated greater potential for development elasticity and transitional advantages compared to oil and coal in the context of energy transition [1]. It plays a pivotal role in power system peaking, heat system supply, and emission reduction in the industrial field [2]. In line with the promotion of energy saving and emission reduction in China, the heat supply structure is undergoing a gradual transformation towards a greener and lower-carbon model. By the conclusion of 2022, Beijing's urban heat supply had established a relatively stable system, effectively achieving a clean heat supply. This predominantly comprised gas boilers for centralized heat supply and gas-fired cogeneration, with district gas boiler rooms serving as the primary source of heating for 68.10% of the area.

Natural gas is a clean energy source, and the flue gas produced after complete combustion is relatively simple in composition and has few pollutants, with large water vapor content, which is the main carrier of flue gas heat. Discharging this high-temperature flue gas with high humidity into the atmosphere without treatment will result in a large amount of wasted latent heat resources for the flue gas [3]. The upscaling of waste heat energy has been proposed as an effective solution to utilize low-grade waste heat; absorption heat pump technology has been shown to reach a relatively high level of upscaling with a considerable coefficient of performance [4]. If the water vapor in the flue gas composition can be condensed during the flue gas discharge process, and the latent heat of condensation can be recovered and utilized, the thermal efficiency of the gas boiler can be improved [5], and the theoretical thermal efficiency can reach 100% or even more [6]. D.M. van de Bor et al. [7] used thermodynamic modeling to focus on the potential of several waste heat recovery technologies in the flue gas temperature range of 45∼60 °C, and they found that heat pump technology is more advantageous in the flue gas temperature range of 45∼60 °C. Jialin Hou et al. [8] proposed a new type of absorption heat pump–boiler system, and the results showed that the heat recovery of the system was 3.8 MW, while 1.14 million m^3 of natural gas could be saved during the heating season. The boiler efficiency was improved by about 11.8%, the condensate recovered was 1177.34 m^3, and it could reduce carbon dioxide emissions by 227 tonnes annually. Zhaoyang Li et al. [9] developed an integrated waste heat recovery system combining a packed tower, an industrial turbine, and an absorption heat pump for coal-fired boilers; this system achieved energy laddering, energy saving, and pollutant emission reduction. Zhang Qunli et al. [10] proposed a spray-tower-type flue gas condensation waste heat recovery and low nitrogen emission synergistic treatment technology approach. It can not only efficiently recover flue gas condensation waste heat but also effectively reduce the concentration of nitrogen oxide emissions. Sun Jian et al. [11] developed electric heat pumps and wall-type heat exchangers to recover the flue gas waste heat of a natural gas boiler. The experimental results show that, on average, this exhaust heat recovery system can be used to reduce energy consumption and pollutant emissions. Their results show that the average exhaust temperature of the system is 33.1 °C, which can raise the heat network return water temperature from 42.9 °C to 60.0 °C on average, and the flue gas whitening effect is obvious. Cai et al. [12] proposed a novel, double-section, full-open absorption heat pump driven by flue gas from the desulfurization tower. This system, by designing the absorber with a double-layer structure, effectively recovers flue gas waste heat within the temperature range of 30–70 °C, significantly enhancing its thermal recovery capability.

The recovery of latent heat from boiler flue gases is a field worthy of further research and attention. In waste heat recovery technology, the application of heat exchange technology is mainly divided into the indirect heat transfer method and the direct-contact heat transfer method, both of which utilize the temperature difference to realize waste heat recovery [13]. The direct-contact heat exchange method is also known as the spray condensation method; its structure is simple, and it achieves high heat exchange efficiency, but the cooling water and flue gas direct contact is acidic and contains dust, a desulfurization agent, desulfurization gypsum, and other substances, which can easily cause clogging in the spray system, as well as the corrosion of pipelines and heat utilization equipment [13,14]. The indirect heat exchange method increases the corrosion-resistant indirect cold heat exchanger in the flue, which has a simple structure and low initial investment but requires a larger heat exchange area and increases the flue gas flow resistance, thus increasing the fan energy consumption. Low-grade waste heat has some disadvantages in various industries, and it is difficult to utilize the low temperature of waste heat. This paper combines indirect heat exchange technology and waste heat upgrading and utilization technology, through the multi-stage heat exchanger in series, with the heat pump technology of low-grade energy upgrading and utilization to achieve flue gas down to the dew-point temperature below the discharge and complete the flue gas depth-condensation waste heat recovery. The configuration of waste heat depth recovery technology allows for an improvement in boiler thermal efficiency, which can be achieved without an increase in demand. This results in a reduction in energy consumption and total emissions. Additionally, the precipitation of condensate in the flue gas facilitates the removal of condensate and the absorption of pollutants, further reducing pollutant emissions. It is, therefore, evident that research into the recovery of flue gas waste heat, particularly the utilization of latent heat resources within flue gas, with the objective of achieving comprehensive heat recovery from flue gas, represents a mutually beneficial endeavor for the environment and for economic gain.

2. Materials and Methods

2.1. Baoneng Heating Plant Introduction

The Beijing Baoneng Heating Plant is used as a case study in this paper to design a flue gas waste heat recovery system in depth and to carry out experiments. The heating area of the residential building complex surrounding the heating plant is 86,000 m^2, and the thermal index of the building design is 60 W/m^2. The design of the system was undertaken in accordance with the " Code for thermal design of civil building (GB50176-2016)" [15], the design daily heating time in Beijing is 24 h, and the calculated temperature of the outdoor heating in winter is −7.6 °C. The mean outdoor temperature during the heating period is −1.6 °C, and the calculated indoor temperature is set to 18 °C, with the heating period lasting 120 days. The temperature distribution in Beijing during the heating season is illustrated in Figure 1, as depicted in the operation records of the Baoneng Heating Plant.

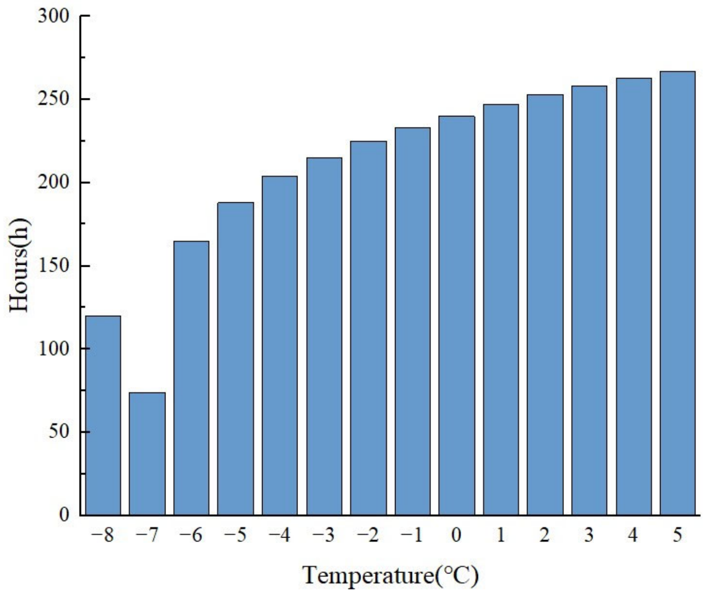

Figure 1. Climate distribution of heating season in Beijing.

The Baoneng Heating Plant is responsible for the provision of steam to the Beijing West Railway Station, with the principal function of meeting the station's heating demands during winter, air-conditioning requirements in summer, and domestic hot water supply throughout the year. The plant is equipped with four natural gas steam boilers, including two boilers with a capacity of 75 t, one boiler with a capacity of 45 t, and one boiler with a capacity of 35 t. The boilers operate on a year-round basis, providing an average of 120 t/h of steam to the West Railway Station in winter and 80 t/h of steam in summer. During the transitional season, the provision of domestic hot water is the primary function, requiring a comparatively modest amount of steam, with an average steam quantity of less than 30 t/h.

The four boilers at the Baoneng Heating Plant have been employed to achieve primary energy savings through the utilization of waste heat, thereby reducing flue gas emission temperature from approximately 270 °C to 140 °C. The present paper combines the actual operating conditions of the Baoneng Heating Plant, the design of a stepped flue gas waste heat recovery system combined with heat pump technology, and the transformation of the original equipment based on the site.

2.2. System Description

The flue gas discharge temperature of the gas boiler at the Baoneng plant is 140 °C, and the dew-point temperature of the flue gas is 56 °C. This indicates a significant potential for the recovery of sensible and latent heat resources for waste flue gas. The configuration of the flue gas depth-condensation waste heat recovery system, as delineated in Figure 2, involves the implementation of a stepped flue gas heat exchanger device that facilitates the graded utilization of flue gas heat. The system employs heat pump technology to upgrade low-temperature flue gas heat, thereby achieving the recovery and utilization of flue gas waste heat.

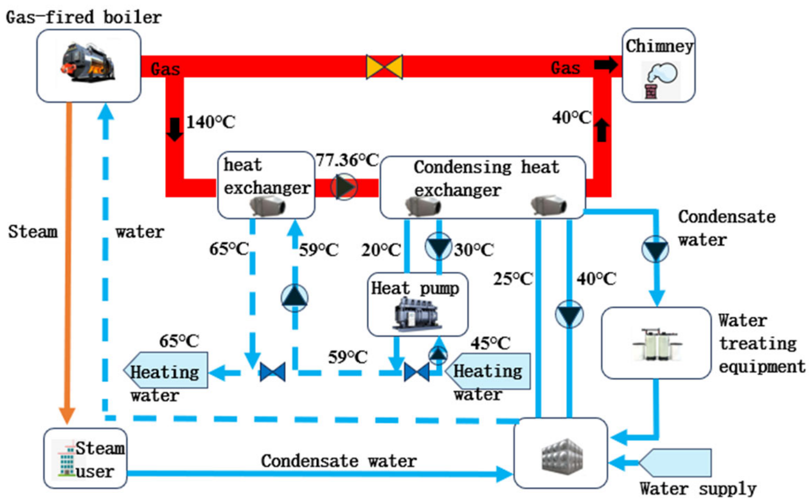

Figure 2. Detailed design of the deep-condensation waste heat recovery system for flue gas at Baoneng Heating Plant.

The original flue of the gas boiler is opened, and the flue gas is controlled to flow into the high-temperature heat exchanger for cooling. The heat recovered at this time is the sensible heat of the flue gas. Then, via frequency conversion-induced draft fan pressure, flue gas enters into the low-temperature condensing heat exchanger to release a large amount of the flue gas's latent heat. After being cooled, the flue gas passes through the flue to the chimney discharge. The heat network return water enters the absorption heat pump equipment through the frequency conversion pump, and high-temperature steam drives the heat pump unit to transfer the heat of the intermediary water to the heat network return water. After that, the heat network water enters the high-temperature heat exchanger to be heated until it reaches the heating design temperature. After the heat of the intermediary water is absorbed via the heat pump, it enters the low-temperature heat exchanger again to recover the low-grade waste heat of the flue gas in a low-temperature state, and the cycle continues.

2.2.1. High-Temperature Intermetallic Wall-Type Heat Exchangers

Flue gas that is produced via high-temperature flue gas waste heat recovery and that reaches above the dew-point temperature of the flue gas waste heat (from 140 °C down to 80 °C) releases flue gas sensible heat. Since the flue gas temperature in the process is higher than the dew-point temperature of the flue gas, there is no need to consider the corrosion problem. In order to ensure better heat transfer efficiency and reduce construction costs, a high-temperature wall-type heat exchanger of conventional metal is used to heat the heat network return water from the heat pump unit until it reaches the heating design temperature during the second heating.

2.2.2. Modified Polypropylene Heat Exchangers for Low and Medium Temperatures

The waste heat recovery of medium- and low-temperature flue gas is achieved by connecting two modified polypropylene condensing heat exchangers in series to heat the boiler make-up water and the intermediate water of the heat pump unit, respectively. The medium-temperature flue gas flows through the heat exchanger and becomes low-temperature flue gas after heating the boiler make-up water by using the temperature difference. Then, it exchanges heat with the intermediary water of the absorption heat pump, and the heat pump unit then extracts the heat in the intermediary water and uses it for the primary heating of the heat network return water.

For the recovery of latent heat from flue gas, since the flue gas contains some pollutants, the main difficulty lies in the poor corrosion resistance of metal heat exchangers with high heat transfer coefficients and good heat transfer performance. As a result, the system cannot meet the engineering requirements for a long service life of the heating system and for a low failure rate. Waste heat recovery technology has developed to the present in order to satisfy the demands of a variety of different scenarios of heat transfer requirements; as a result, an increasing number of methods for achieving anti-corrosion are used in the design and manufacture of heat exchangers. Polymer materials have the advantages of low density, corrosion resistance, anti-scaling, strong plasticity, etc. Thus, in non-metallic heat exchanger applications in a low- and medium-temperature environment, these materials find wide application and excellent market potential. Technoform Kunststoffprofile GmbH (Lohfelden, Germany) manufactures polypropylene as a substrate; it is filled with graphite, and then the company uses a special process to produce modified polypropylene heat exchanger tubes. Experimental studies have demonstrated that the composite material exhibits the best relationship between thermal conductivity and mechanical properties for heat exchangers when about 50 vol% of graphite filling is used [16].

Therefore, in the process of medium- and low-temperature flue gas waste heat recovery, the selection of a modified polypropylene heat exchanger with excellent heat transfer performance, corrosion resistance, and anti-scaling properties is essential. This exchanger can be combined with absorption heat pump technology to complete deep flue gas waste heat recovery. Not only can such an exchanger significantly improve the boiler efficiency of gas boilers and reduce the use of primary energy, but a large amount of condensate can be recovered, thereby reducing the emission of pollutants such as nitrogen oxides and smoke particles. This exchanger demonstrates other positive effects on environmental protection as well.

2.2.3. Absorption Heat Pump Units

As the core equipment in the flue gas waste heat recovery system, the heat pump can control how much heat is extracted from the intermediary water and heat the return water of the heat network to the set temperature, which greatly enhances the adjustable function of the flue gas waste heat recovery system. In this study, we combined the characteristics of the Baoneng Heating Plant with sufficient steam and applied the Huayuan Taimeng HRU series of waste heat recovery heat pump units—also known as heat-boosting heat pumps—in addition to a generator–condenser, an evaporator–absorber, a solution heat exchanger, solution pumps, refrigerant pumps, automatic pumping and exhausting devices, a color display control screen, etc. Lithium bromide absorption heat pumps were connected to three closed loops, namely the heat network water input and output loop, the intermediary water input and output loop, and the steam input and output loop. This connection greatly enhanced the regulation of the flue gas waste heat recovery system. The three loops were not mixed in the equipment; each was independent.

HRU series waste heat recovery units use a small amount of high-temperature steam-driven lithium bromide-absorption heat pump (COP $\geq$ 1.58) to enhance the flue gas waste heat grade and restore heat to the heat network return water. It also improves the efficiency of heat utilization and accomplishes the recovery of low-grade waste heat from the flue gas, resulting in a significant increase in heating capacity and system economics.

2.3. Experimental Data Measurement and Processing

2.3.1. Measured Content

It is imperative to meticulously measure the input and output temperatures of the flue gas flowing through each heat exchanger, as well as the input and output temperatures of the cooling water in each heat exchanger. Furthermore, the input and output temperatures of the heat pump unit must be measured, as must the temperatures of the supply and return water of the heat supply pipeline network.

2.3.2. Measurement Point Layout

(1) With regard to the detection of flue gas temperature, temperature measurement points are to be set at the flue locations of the flue gas inlet and outlet of each heat exchanger.

(2) In the context of water temperature monitoring, temperature measurement points are to be set at the piping location of the water flow inlet and outlet of each heat exchanger.

(3) In the context of lithium bromide absorption heat pump units, temperature measurement points are set at the input and output positions of the heat source and heat user sides, respectively.

(4) Temperature measurement points are set at the inlet and outlet of the supply and return water pipelines of the heat supply pipeline network.

2.3.3. Data Processing

(1) During the operation of the system, the waste heat recovery automatic control system is responsible for the real-time recording of data from each measurement point, which is then uploaded to the main console of the heating boiler at a data recording interval of 15 min.

(2) Data that exhibit a significant deviation from the actual value will be deleted during the data processing stage. The remaining data will then be organized in the form of charts for the purpose of comparative analysis.

2.4. Calculation of Flue Gas Heat Transfer

Using Beijing Baoneng Heating Plant as the research object, the flue gas flow rate of the gas boiler of Baoneng Heating Plant was 60,000 Nm^3/h, and the temperature of the exhaust smoke was 140 °C. The plant's energy-saving potential was analyzed.

2.4.1. Calculation of Flue Gas Sensible Heat Recovery

Using a waste heat recovery device for a high-temperature wall-type flue gas heat exchanger, we measured the flue gas temperature to be higher than its dew-point temperature, and there was no condensate precipitation. The recovered heat is the flue gas's sensible heat. The results of the calculation using Equation (1) (from 140 °C down to various sensible heats of the exhaust flue gas) can be seen in Table 1.

$$Q_X = C_p m (T_i - T_0) \tag{1}$$

where Q_X is the sensible heat released via the flue gas during the cooling process (kW), C_p is the constant pressure-specific heat capacity of flue gas (kJ/(kg·K)), m is the mass flow rate of flue gas (kg/s), T_i is the temperature of flue gas at the inlet of the heat exchanger (K), and T_0 is the temperature of the flue gas at the exit of the heat exchanger (K).

Table 1. Sensible heat released via flue gas at different exhaust temperatures.

Exhaust Temperature (°C)	140	80	60	50	40	30	20
Recoverable volume (MW)	0	1.446	1.953	2.182	2.433	2.664	2.883
Boiler efficiency improvement (%)	0	3.16	4.27	4.77	5.32	5.82	6.30

2.4.2. Calculation of Flue Gas Latent Heat Recovery

Flue gas latent heat is the water vapor in the flue gas in the condensation process of the release of latent heat of water vapor. This part of the heat should be equal to the latent heat of the vaporization of water vapor, and this part of the heat flue gas depth reveals the depth of the waste heat recovery of the main target. In order to ensure the accuracy of the calculation, in this study, we used the amount of condensate to calculate the amount of flue gas latent heat recovery; this was calculated using Equations (2)–(4) for the different exhaust temperatures under the recovery of flue gas latent heat, as shown in Table 2.

$$Q_q = m_{s,n} \cdot \gamma_i \tag{2}$$

where Q_q is the latent heat released via flue gas at different exhaust temperatures (kJ), and γ_i is the latent heat of the vaporization of water vapor at different exhaust temperatures (kJ/kg).

Table 2. The latent heat released via flue gas at different exhaust temperatures.

Exhaust Temperature (°C)	60	50	40	30	20
Condensation (kg/s)	0	0.630	1.305	1.696	1.921
Condensation ratio (%)	0	28.80	59.68	77.56	87.88
Latent heat recovery (MW)	0	1.500	3.139	4.121	4.716
Boiler efficiency improvement (%)	0	3.28	6.86	9.00	10.31

When the flue gas temperature drops below the dew-point temperature, the water vapor in the flue gas will precipitate as condensate, at which time the latent heat of the flue gas can be recovered. The calculation of the amount of condensate at the exhaust temperature is shown in Equation (3):

$$m_{s,n} = m_{y,g} \cdot \left(d_{y,L} - d_{y,p}\right) \tag{3}$$

where $m_{s,n}$ is the condensate water quality at different exhaust temperatures (kg), $m_{y,g}$ is the mass flow rate of dry flue gas (kg/s), 18.52 kg/s [17], $d_{y,L}$ is the moisture content of the flue gas at dew-point temperature (g/kg), and $d_{y,p}$ is the moisture content of flue gas at exhaust temperature (g/kg).

The moisture content of the flue gas is denoted as the symbol d. The calculation is simplified using the ideal gas equation; see Equation (4):

$$d = 605.56\frac{P_v}{P_a} \tag{4}$$

where d is the moisture content of flue gas (g/kg), P_v is the sub-pressure of water vapor (Pa), and P_a is the partial pressure of dry flue gas (Pa).

The partial pressure of water vapor in the flue gas of the gas boiler of the Baoneng Heating Plant is calculated to be 16.434 kPa, and by consulting the table of the physical properties of saturated water and saturated water vapor, it can be seen that the dew-point temperature of the flue gas is 56 °C. And when the flue gas drops below the dew-point temperature, the change in the flue gas mass flow rate leads to a smaller error in the amount of sensible heat, so it is negligible.

2.4.3. System Key Equipment Selection

Through the previous calculation of the waste heat recovery potential of the gas boiler flue gas of Baoneng Heating Plant, the relationship between improvement in boiler thermal efficiency and different exhaust temperatures is shown in Figure 3.

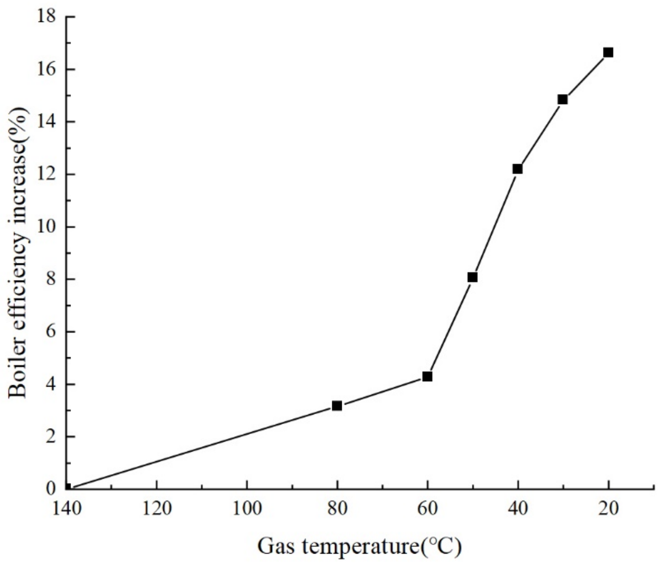

Figure 3. The relationship between total heat recovered and boiler thermal efficiency at different exhaust temperatures.

As can be seen from Figure 3, the flue gas sensible heat recovery increases linearly with a decreasing exhaust temperature, but its growth is slow. At an exhaust temperature of 60 °C, for example, all the heat recovered from the flue gas sensible heat (a temperature difference of 80 °C) can only increase the thermal efficiency of the boiler by 4.27%. When the temperature of the exhaust drops below the dew-point temperature, a large amount of latent heat is released via water vapor condensation. When the exhaust temperature reaches 50 °C (at which point, there is a difference of 6 °C between the exhaust temperature and the dew-point temperature), it is only the latent heat recovery of the flue gas that makes the thermal efficiency of the boiler increase by 3.28%.

The flue gas precipitates about 60% of the condensate when the dew-point temperature drops from 56 °C down to 40 °C. This indicates that the latent heat of the flue gas released by a temperature difference of only 16 °C is 1.3 times the amount of sensible heat of the flue gas released by a temperature difference of 100 °C. Consequently, the sensible and latent heat recovered a total of 5.57 MW of heat, which has the potential to increase the boiler efficiency by 12.18%. However, in the process of the exhaust temperature dropping from 40 °C to 20 °C, only about 28% more condensate in the flue gas can be precipitated, and the increased amount of latent heat recovery can increase the boiler thermal efficiency by 3.44%, which only accounts for 1/2 of the increase in thermal efficiency brought about via the reduction from 56 °C to 40 °C. A lower exhaust temperature means a significant increase in the difficulty of recovery and rising construction costs; thus, the heat cannot be dissipated enough to meet the heat demand of the Baoneng Heating Plant while ensuring waste heat recovery. It is important for the boiler to recover the heat from the exhaust temperature so as to meet the heat demand of the plant and, at the same time, to ensure that waste heat recovery is carried out as designed. In order to meet the heat demand of Baoneng Heating Plant and to ensure that the waste heat recovery system is constructed economically, it is more reasonable to use a final exhaust temperature of 40 °C in the design.

We examined the construction conditions of Beijing Baoneng Heating Plant and investigated its heating season operation records to determine the design temperature of the heat network supply and return water for 65 °C and 45 °C, respectively. The heating network water supply flow rate was 210 t/h, and the maximum heat load of the heating season was 4.90 MW. We used these measurements as a basis for designing a flue gas heat recovery system and a feasible flue gas depth-condensation waste heat recovery system. The key equipment types and parameters are shown in Table 3.

Table 3. Key equipment types and parameters.

Thematic	Equipment Name	Equipment Type and Parameters	Maximum Equipment Load
First level	High-temperature heat exchangers	Type: wall-type heat exchanger Material: metal (316L) High-temperature flue gas: (140–77.36 °C) Heating network return water: 59–65 °C	1.46 MW
Second level	Condensing heat exchangers	Type: shell and tube heat exchanger Material: non-metallic (modified polypropylene) Medium-temperature flue gas: 77.36–50 °C Boiler make-up water: 25–40 °C	2.28 MW
	Condensing heat exchangers	Type: shell and tube heat exchanger Material: non-metallic (modified polypropylene) Low-temperature flue gas: 50–43 °C Intermediate medium-temperature water: 20–30 °C	1.33 MW
	Absorption heat pump units	Type: shell and tube heat exchanger Driving mode: high-temperature steam drive Heat pump unit COP: 1.58 Intermediate medium-temperature water: 30–20 °C Heating network return water: 45–59 °C	3.44 MW

2.5. Energy Efficiency and Environmental Benefits

2.5.1. Energy Saving Benefits

The total amount of heat recovered during the heating season (120 days) can be calculated as follows:

$$Q = W_{max} \cdot T \quad (5)$$

where Q is the total heat recovered in the heating season (J), W_{max} is the maximum waste heat recovery power (W), and T is the heating time (h).

2.5.2. Environmental Benefits

Flue gas waste heat recovery to reduce direct carbon emissions can be calculated based on the amount of flue gas waste heat recovered, converted to direct carbon emissions from natural gas combustion via a gas boiler. The calculation process is as follows:

$$m_{co_2} = \mathrm{Q} \cdot E \cdot F \cdot N \tag{6}$$

where m_{CO_2} is the emission of CO_2 from the gas boiler (kg), Q is the fuel heat (GJ), E is the carbon content per unit calorific value (kg/GJ), 15.30 kg/GJ; F is the carbon oxidation rate, 0.99, and N is the molecular weight ratio of CO_2 to carbon.

The flue gas waste heat recovery system results in indirect emissions, primarily in the form of carbon emissions associated with the generation of electricity. These emissions are quantified as follows:

$$m'_{co_2} = \mathrm{W} \cdot F_g \tag{7}$$

where m'_{CO_2} is the indirect carbon emission (kg), W is the annual electricity consumption (kWh), and F_g is the indirect emission factor (kg/kWh), assumed to be 0.604 [18].

3. Results

The experiments on the waste heat recovery system were carried out under the actual operating conditions of the boiler. As the ambient temperature rises at the end of the heating period, Baoneng Heating Plant adjusts the water supply temperature of the heat network to 60 °C and the flow rate to 190 m^3/h in order to guarantee the comfort of the heat users. In its experimental stage, the flue gas deep waste heat recovery system should meet the requirement of heating the return water of the heat network to 60 °C and guaranteeing the stable operation of the heating system, and the experiments of the waste heat recovery system are carried out on this basis. This allows us to analyze the following data related to the heat pump operation under working conditions: exhaust temperature, heat network supply, return water temperature, and other key data.

3.1. Absorption Heat Pump Unit Data

In the experimental flue gas waste heat recovery system, the absorption heat pump unit is the core control equipment of the flue gas deep-condensation waste heat recovery system. A high-temperature steam drive enhances the energy grade of the intermediary water and transfers it to the heat network return water. The application of the heat pump self-control system directly controls the outlet temperature of the water of the heat network, and this temperature can be regulated according to the external demand in order to achieve stability, safety, and high efficiency in the operation of the waste heat recovery system. The design coefficient of performance (hereinafter referred to as COP) of this equipment is 1.58, the design flow rate of the intermediary water on the heat source side is 115 t/h, and the actual operating flow rate is 105 t/h. The design flow rate of the heat network on the user side is 210 t/h, and the actual operating flow rate is 190 t/h. The outlet temperatures of the heat network water of the heat pump equipment were set to be 54 °C, 55 °C, and 56 °C during the experimental period. Figure 4 shows the data for 29 January 2024, 30 January 2024, and 31 January 2024 because these dates took place after the completion of the project and the weather was cold, so it could be a better representation of the recovery effect of the waste heat system. The rapid rise and fall of the experimental data were the beginning and the end of the experiment, respectively; the heat supply plant will be switched to the flue gas after the waste heat recovery system, and the system can be converted to a continuous and stable operation after about 30 min. When the equipment is running stably, although the input temperature of the heat network return water varies greatly with the ambient temperature and heating heat load, the heat pump control system can adjust the equipment load so that the output temperature of the heat network return water is raised to the experimental setting temperature and runs stably. In this manner, the maximum temperature difference between the input and output temperature of the intermediate water on the heat source side is 5.07 °C, and the minimum input and output temperature difference is 0.97 °C. The maximum input and output temperature difference in heat network return water heated via the heat pump equipment is 8 °C, and the minimum input and output temperature difference is 1.5 °C. As shown in Figure 5, the COP value of this equipment is 1.58, on average, after stable operation, which is in line with the design objective. According to Figure 4, it can be seen that the temperature difference between the input and output of the intermediary water is related to how high the heat pump control system temperature of the heat network return water outlet is set. When the ambient temperature is low and the heating heat load is large, raising the temperature of the heat pump equipment's heat network return water outlet setting increases the load and output of the heat pump equipment, transferring more heat from the intermediary water to the heat network return water, which can keep the intermediary water continuously exchanging heat with the flue gas at a lower temperature. On the contrary, if the external heating heat load is small, the heat in the intermediary water cannot be absorbed in time, which will lead to intermediary water heat accumulation, and the temperature of the water will gradually increase, eventually reaching close to thermal equilibrium with the flue gas. From the experiment, it can be seen that the device can be used as the core heating equipment in the cold period not only to provide a stable heat network return water temperature in an extreme environment but also, indirectly, to more efficiently achieve the effect of boiler flue gas depth cooling.

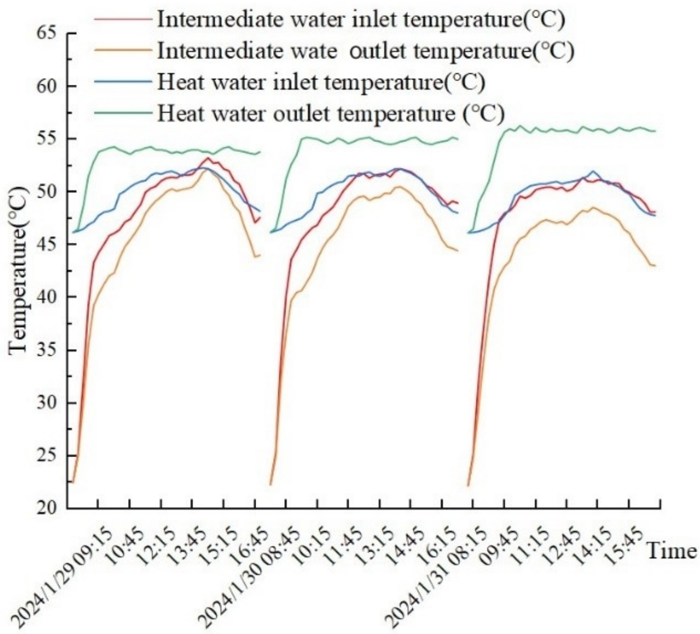

Figure 4. Lithium bromide absorption heat pump system inlet and outlet temperatures.

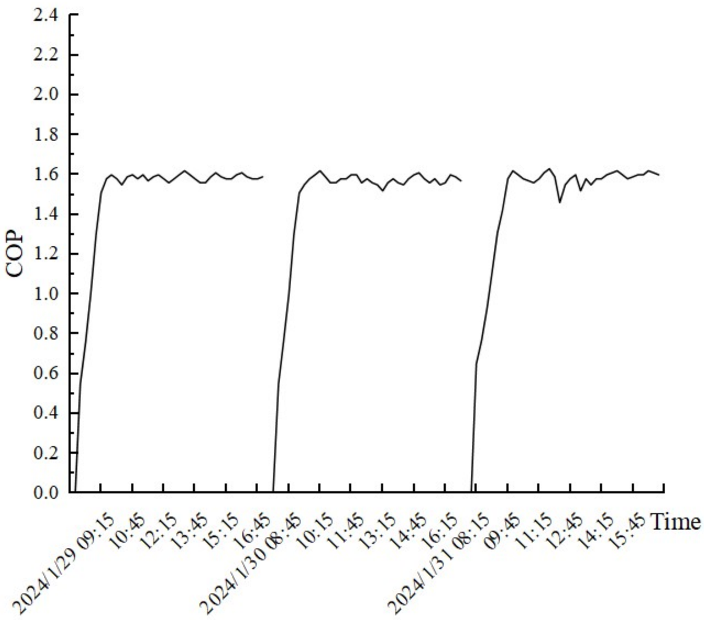

Figure 5. Coefficient of performance (COP) for lithium bromide-absorption heat pump units.

3.2. Flue Gas Temperature

The deep recovery of flue gas waste heat employs heat pump technology and waste heat step recovery technology to carry out the utilization of low-grade heat from the flue gas. Firstly, the flue gas is high-temperature flue gas when it is discharged from the boiler tail, and it is cooled down to medium-temperature flue gas via the return water of the heat network in the high-temperature metal wall-type heat exchanger. Subsequently, it enters the modified polypropylene heat exchanger, first exchanges heat with the boiler make-up water to become low-temperature flue gas, and finally is cooled via the low-temperature intermediary water on the heat pump side to the flue gas temperature and discharged into the atmosphere.

The external ambient temperature decreased day by day during the experimental period, and according to the experimental data, the lowest chimney exhaust temperature occurred at 9:00 a.m. on the third day of the experiment. This occurred during the lowest ambient temperature period of the experimental period, with the flue gas temperature at the end of the boiler at 146 °C and the chimney exhaust temperature at 47.5 °C. The lowest chimney exhaust temperature was at 2:45 p.m. on the first day of the experiment. This occurred during the highest ambient temperature period of the test period, with the flue gas inlet temperature at 147 °C and the chimney exhaust temperature at 53.2 °C.

As shown in Figure 6, in the experimental system, after the equipment operation is stabilized, the flue gas passes through the waste heat recovery system, with a maximum temperature difference between input and output of 98.5 °C, a minimum temperature difference between input and output of 90.4 °C, an average inlet temperature of 144.62 °C, and an average outlet temperature of 51.84 °C, which is higher than the design temperature of 40 °C. The reason was analyzed as mentioned above: as the heating heat load is small, the intermediary water and the flue gas reach a thermal equilibrium state, and there is no longer a cooling effect on the flue gas. The phenomenon will be significantly improved under the working conditions in the severe cold period.

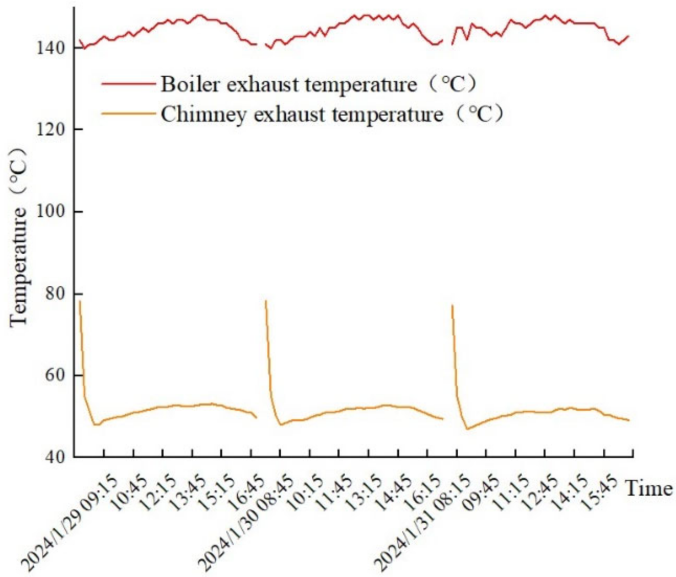

Figure 6. Temperature difference between inlet and outlet of waste heat recovery system flue gas.

3.3. Changes in Supply and Return Water Temperatures in the Heat Network

The variation of supply and return water temperatures in the heat network during the experimental period is shown in Figure 7. The heat pump equipment, which controls the heat network return water outlet temperature, was set to 54 °C, 55 °C, and 56 °C. During the experimental period, the daily average heat network water supply temperature of the heat network return water heated via the high-temperature wall-type flue gas heat exchanger was set to 59.79 °C, 60.78 °C, and 61.84 °C to achieve stable heat in order to meet the demand for heat supply. The difference between the maximum heat network supply and the return water temperature was 14.3 °C, and the difference between the minimum heat network supply and return water temperature was 7.6 °C. The greatest differences between the supply and return water temperatures occurred from 8:00 a.m. to 10:00 a.m. and from 3:00 p.m. to 5:00 p.m. every day. At these times, the ambient temperatures are lower, and the heating heat load is larger, corresponding to an increase in heat network supply and the return water temperature difference. As the ambient temperature rises, the temperature difference gradually decreases, and the difference between the temperature of the supply and return water decreases to a minimum from 12:00 a.m. to 2:00 p.m. daily. The difference in the temperatures of the supply and return water shows a trend of increasing day by day due to the lowering of the ambient temperature and the gradual increase in the heating load during the experimental period.

In the design calculations for the flue gas deep-condensation waste heat recovery system, the heating heat load was designed in accordance with the maximum load calculations for the Beijing cold period, the heat network water flow rate was designed to be 210 t/h, the temperature difference between the supply and return water was 20 °C, and the actual operating flow rate was 190 t/h. According to the operating data, it can be seen that the experimental period of the heat load was designed under the condition of achieving an efficiency of 34% to 65%, which would provide evidence that the experiment affects the heating heat load. This confirms that, in the experiment, because the heating heat load was small, the quantity of gas boiler make-up water was small. As a result, the boiler make-up water in the heat exchanger cycle was heated via the flue gas, producing an increasing temperature. Furthermore, the intermediate, medium-temperature, water-absorbed flue gas heat could not be quickly dissipated, and the continuous rise in temperature resulted in a decline in the effect of the cooling of the flue gas. In summary, when the flue gas deep-condensation waste heat recovery system is in stable operation, the flue gas waste heat from the gas boiler of the Baoneng Heating Plant can be utilized to provide controllable, stable, safe, and highly efficient heat to bring the heat network return water up to the design temperature of the heat supply by combining the heat pump technology with the ladder heat exchanger. This guarantees the high quality and stable operation of the heating project at all stages during the heating period.

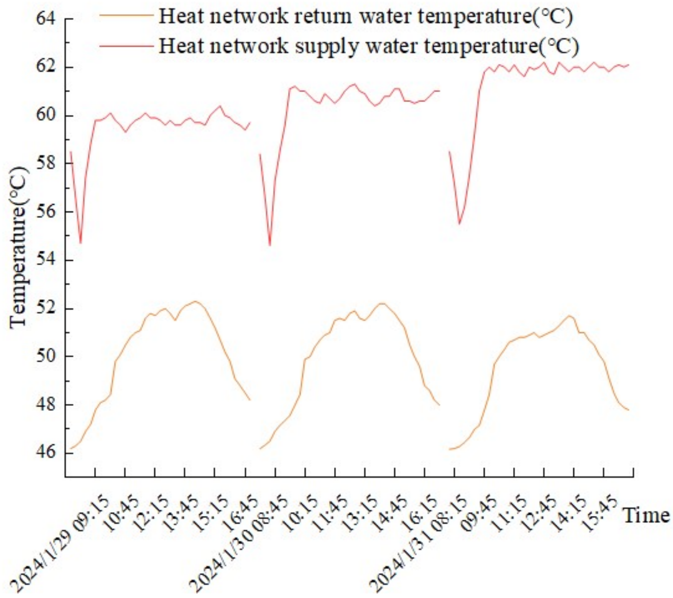

Figure 7. Variations in supply and return water temperatures in the heat supply network during operation.

3.4. Analysis of Energy-Saving and Economic Benefits

3.4.1. Analysis of Energy Efficiency Benefits

Baoneng Heating Plant uses 60,000 Nm^3/h flue gas, which ranges in temperature from 140 °C to 40 °C. The maximum power of its waste heat recovery is 5.57 MW, and it is capable of increasing the thermal efficiency of its boiler by 12.17%. In the case of a heating period of 120 days, the total heat recovery in the heating season is 57,800 GJ, as calculated through Equation (5).

It is evident that, in consideration of the low calorific value of natural gas (35 MJ/Nm^3), this is indicative of an annual reduction of approximately 1,650,800 Nm^3 in natural gas. According to the design of Huayuan Taimeng, the total heat consumed via the absorption heat pump unit during the heating season is 21,900 GJ, which increases the gas consumption by 625,000 Nm^3.

In addition, due to the flue gas deep waste heat recovery system put into operation, the increase in variable frequency fans, circulating water pumps, heat pump units, and other equipment resulted in an increase in the heating plant's power consumption during the heating season. According to our calculations, this equipment used a total of 168 kW of total electrical power. The total power consumption during the heating season was 483,800 kWh, equivalent to 49,800 Nm^3 of natural gas.

In summary, the construction of a flue gas deep-condensation waste heat recovery system can save a net gas volume of 976,000 Nm^3 during the annual heating season. A total of 13,500 tonnes of flue gas can be recovered through the precipitation of condensate. Under regular operating conditions at the Baoneng Heating Plant, the recovered condensate can be used as boiler make-up water after purification, and the treatment can be completely consumed.

3.4.2. Analysis of Environmental Benefits

Flue gas waste heat can be converted into direct carbon emissions from gas boilers by referring to the direct emission standards for gas boilers. The calculation process is shown in Equation (6). For the Baoneng Heating Plant's flue gas waste heat recovery system, during the heating season, 57,800 GJ of flue gas waste heat was recovered, and a total of 3213.07 t of discounted direct carbon emissions were recovered from the gas boiler.

The use of the flue gas waste heat recovery system leads to indirect emissions, which mainly refer to carbon emissions that are in the process of producing electricity, as can be seen from the analysis of energy-saving benefits. The construction of a flue gas waste heat recovery system for the Baoneng Heating Plant will lead to a new annual power consumption of 483,800 kWh, thus indirectly leading to carbon emissions of 292.22 t. The calculation process is shown in Equation (7).

From the above analysis, it can be seen that the following results were observed at Baoneng Heating Plant after the construction of a flue gas deep waste heat recovery system: an annual reduction in direct carbon emissions of 3213.07 t, an annual increase in indirect carbon emissions of 292.22 tCO_2, and, ultimately, an annual net reduction in carbon emissions totaling 2920.85 t.

3.4.3. Analysis of Economic Benefits

In the economic analysis of the heating season, the price of natural gas is CNY 2.88/Nm^3 [19]. Baoneng Heating Plant uses large-scale industrial electricity, which costs CNY 0.65/kWh during the heating season based on the weighted average price of electricity in January. The price of water is CNY 12/t, and the carbon trading fee is CNY 50/t. An economic benefit analysis of Baoneng Heating Plant in the heating season is shown in Table 4, and the construction of the flue gas deep-condensation waste heat recovery system can reduce the total operating cost of Baoneng Heating Plant in the heating season by CNY 2,947,800.

Table 4. Comparison of economic benefits of flue gas waste heat recovery system during heating season.

Name	Pre-Construction	Post-Construction
Calorific source	Gas flaring	Flue gas waste heat and natural gas combustion
Total heat output of the system	57,800 GJ	57,800 GJ
Type of energy consumption	Petroleum	Flue gas waste heat, natural gas, electricity
Calculation of energy consumption	1,650,800 Nm^3	625,000 Nm^3, 483,800 kWh
Calculation of the cost of consumed energy	CNY 4,754,300	CNY 2,114,500
Water bill	CNY 162,000	0
Carbon transaction costs	CNY 146,000	0
Total cost	CNY 5,062,300	CNY 2,114,500

4. Conclusions

Flue gas emissions are an inevitable product of the development of social industrialization. At present, the vast majority of domestic heating gas boiler emissions reach a flue gas temperature above 75 °C; this paper on Baoneng Heating Plant serves as an example of the use of laddering recycling technology and the low-grade energy upgrading use of boiler flue gas from 140 °C can be reduced to a minimum of 40 °C emissions. Moreover, through the experimental verification of the flue gas depth of condensation of waste heat recovery system, the conclusions are as follows:

- Based on the actual operating conditions of the heating plant, one can analyze the potential flue gas waste heat recovery and determine an economically feasible exhaust temperature target. Thus, with 60,000 Nm^3/h flue gas from 140 °C to 40 °C emissions, the recovered flue gas waste heat can meet the heat demands of the surroundings and ensure that the waste heat recovery system is economical. Under these conditions, a maximum increase in boiler efficiency of 12.18% can be achieved.
- The time during which the experiment was carried out was at the end of the heating period, and the heating heat load was only 34–65% of the maximum in the design working condition, resulting in the load of the heat pump being only 48% of the maximum design load. During the experimental period, the flue gas waste heat recovery system ultimately discharged the flue gas into the atmosphere at an average temperature of 51.84 °C. The flue gas heat recovered from the flue gas from 140 °C to this discharge temperature was sufficient to satisfy the heating heat load of the Baoneng Heating Plant during the experimental period.
- The flue gas waste heat recovery system is based on the combination of absorption heat pump technology and stepped waste heat recovery technology. In the season after the completion of the construction of the Baoneng Heating Plant a total of 57,800 GJ of heat was recovered, representing a net saving of 976,000 Nm^3 of natural gas, 13,500 tonnes of recycled water resources, an annual net reduction in carbon emissions of a total of 2920.85 t, and, ultimately, a reduction in the total operating costs during the heating season of the Baoneng Heating Plant of CNY 2,947,800.
- Flue gas waste heat recovery can provide a large amount of heat. The existing heating equipment cannot meet the current heating demand. The original heating system can be directly transformed to significantly increase the heating capacity of the heat source plant without the additional consumption of other energy conditions, thus reducing the cost of the heat supply and improving economic efficiency.
- Flue gas deep heat recovery technology responds positively to China's carbon peaking and carbon neutrality goals, helping promote the use of clean energy, building resource-saving and environment-friendly energy use, and further promoting energy saving, emission reduction, and low-carbon green heating.

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