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Theoretical Design and Analysis of the Waste Heat Recovery System of Turbine Exhaust Steam Using an Absorption Heat Pump for Heating Supply

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Abstract: In northern China, many thermal power plants use absorption heat pump to recover low-grade heat from turbine exhaust steam due to the irreplaceable advantages of the absorption heat pump in waste heat recovery. In the process of designing a waste heat recovery system, few researchers have considered the relationship between the design power of the heat pump and the actual heating load of the heating network. Based on the heating load characteristics, this paper puts forward a design idea which uses an absorption heat pump to recover waste heat from a steam turbine exhaust for heating supply. The operation mode of the system for different design powers of the heat pump was stated. An economic analysis model of the waste heat recovery system was proposed, and the optimal design power of the heat pump could be obtained. For a specific unit, the corresponding waste heat recovery system was designed, and various factors affecting the economy of the system were discussed and analyzed in detail.

Keywords: absorption heat pump; heating load characteristics; design power; waste heat recovery

1. Introduction

Recently, China's urbanization rate has increased considerably and the demand for heating load has increased sharply, especially in large cities in northern China [1]. As an environmentally friendly, efficient energy conversion method, cogeneration can reduce the emission of pollutants and greatly improve the efficiency of primary energy utilization [2]. The central heating method based on cogeneration has been widely used in many cities. Until now, China's urban central heating area has reached 8.78 billion square meters, with an annual growth rate of 12% [3], and the increased heating demand is mainly provided by coal-fired cogeneration plants [4]. In order to supply the increasing heating demand, the heating capacity must be improved [5]. However, constructing new thermal power plants in cities is difficult, owing to the restrictions of China's urban environmental protection policies [6]. At the same time, the existing thermal power plants use large extraction condensing steam turbine units for heating. A great deal of waste heat from low-pressure stage exhaust steam is generally not utilized. Instead, it is discharged into the environment through the circulating cooling water system, resulting in enormous heat loss which accounts for more than 30% of the input energy of the thermal power plant [7,8]. Therefore, the utilization and recovery of waste heat from exhaust steam for heating can save fuel consumption and increase the heating capacity [9]. To date, two methods are mainly used to recover the condensing waste heat from thermal power plants and increase the heating capacity of the heating network substantially [10].

The first method is the low-vacuum operation technology of the steam turbine [9,11,12]. However, the low-vacuum heating operation technology of steam turbines faces two limitations. On the one hand, a high back pressure will reduce the volume flow of the exhaust steam through the low-pressure stage of the turbine, cause turbine vibration, and even endanger the safe operation of the steam turbine unit [13]. On the other hand, according to the principle of determining electricity by heat, the power generation and heating load cannot be adjusted independently, such that the high back pressure unit is only adaptive for occasions with a stable thermal load.

The second technique is using an absorption heat pump to recover waste heat from a steam turbine exhaust. The absorption heat pump uses the high-parameter extraction steam of the steam turbine as a high-temperature heat source and extracts heat from the exhaust steam of the steam turbine as a low-temperature heat source, thereby obtaining medium-grade hot water. Aiming at the current situation of the insufficient heat capacity of the existing heat network, several scholars consider using absorption heat pumps to decrease the return water temperature of the primary heating network dramatically without the need to transform the heating network [14–17]. Usually, the heating system usually has different levels of low-temperature waste heat. Therefore, the absorption heating system should be optimized to recover the waste heat with different parameters [18]. Moreover, conventional thermal power plants usually have multiple units, and the extraction steam, exhaust steam, and heating network water are often not properly matched in terms of quality and quantity, resulting in large irreversible losses [19]. In the case of the combined heating of multiple units, Tian et al. proposed using multiple absorption heat pumps for the cascade utilization of exhaust steam waste heat [20]. In addition, detailed analysis and comparison must be conducted through thermodynamic indicators, because different configurations of the absorption heat pump have varied temperature-raising abilities and efficiencies [21–23]. Xu et al. [24] proposed to connect two single effect absorption heat pumps with different operating parameters in series to achieve a large temperature rise in the heating network. Hu et al. [25] proposed a variable-lift absorption system to heat the return water of the primary heat supply network step by step. Additionally, the outdoor temperature constantly changes during the heating period, which causes the load of the heating network to need to be adjusted accordingly. Some scholars have analyzed the influence of heat load change on the energy efficiency of the absorption heating system and improved the integrated mode of the heating system [26,27].

Most researchers focus on how to recover turbine exhaust heat efficiently and improve the transmission capacity of the heating network by utilizing an absorption heat pump, but few of them consider the relationship between the heat pump power and the heating load of the heating network [28]. During the actual heating period, the heating load changes every day, such that the heat pump system usually runs in off-design conditions. Therefore, the selection of heat pump design power is very important for the waste heat recovery system coupled with absorption heat pump, which has a crucial impact on the efficiency and economy of the system. For these reasons, on the basis of the heating load characteristics, this paper puts forward the design idea of the heating supply system, which uses an absorption heat pump to recover turbine exhaust heat. The operation mode of the heat pump is discussed in four cases according to the design power of the heat pump. An economic analysis model is also proposed to optimize the design power of the heat pump. Combining an engineering example, a heating supply system with waste heat recovery is designed, and the optimal design power of the heat pump is provided. Various factors affecting the economy of the system are discussed and analyzed in detail.

2. Design Idea of Waste Heat Recovery System

2.1. Heating Supply System with Waste Heat Recovery System Using Absorption Heat Pump

In view of the current situation of insufficient heating supply, where a large amount of turbine exhaust heat cannot be effectively utilized, a waste heat recovery system which can utilize absorption heat pump to recover steam turbine exhaust for heating supply is proposed. This system consists of a heater for the heating network and an absorption heat pump. The absorption heat pump in the waste heat recovery system is driven by the high-parameter steam turbine extraction and absorbs the low-grade waste heat from the turbine exhaust steam, thus heating the return water of the heating network. The lithium bromide absorption heat pump is usually used to recover waste heat for thermal power plants. However, due to the limitation of its output performance, the outlet temperature of the absorption heat pump has a maximum value of t'_{hp}. In the following chapters, t'_{po} and t'_{pi} are used to represent the design supply and return the water temperature of the heating network.

In some cases, the outlet water temperature of the absorption heat pump may not satisfy the demands of heat users due to the limitation of its own performance. According to the relationship between the outlet water temperature of the heat pump and the design supply water temperature, there are two connection types of heating system that can be used in different conditions. When the design supply water temperature is larger than the outlet water temperature of the heat pump, the heating supply system is shown in Figure 1a. The outlet water of the heat pump can be heated to a higher temperature in the heater of the heating network and finally delivered to the user side because the heater of heating network and the heat pump are connected in series. According to the heating load and the power of the heat pump, the water of the heating network is partly or fully through the heat pump and fully through the heater for heating network. When the outlet water temperature of the heat pump is greater than the design outlet water temperature of the heating supply network, the heat pump and the heater of the heating network should be connected in parallel, as shown in Figure 1b. In this case, the heat pump and the heater for heating network operate in parallel. Based on the heating load, the heater for heating network is determined to be placed in operation or not.

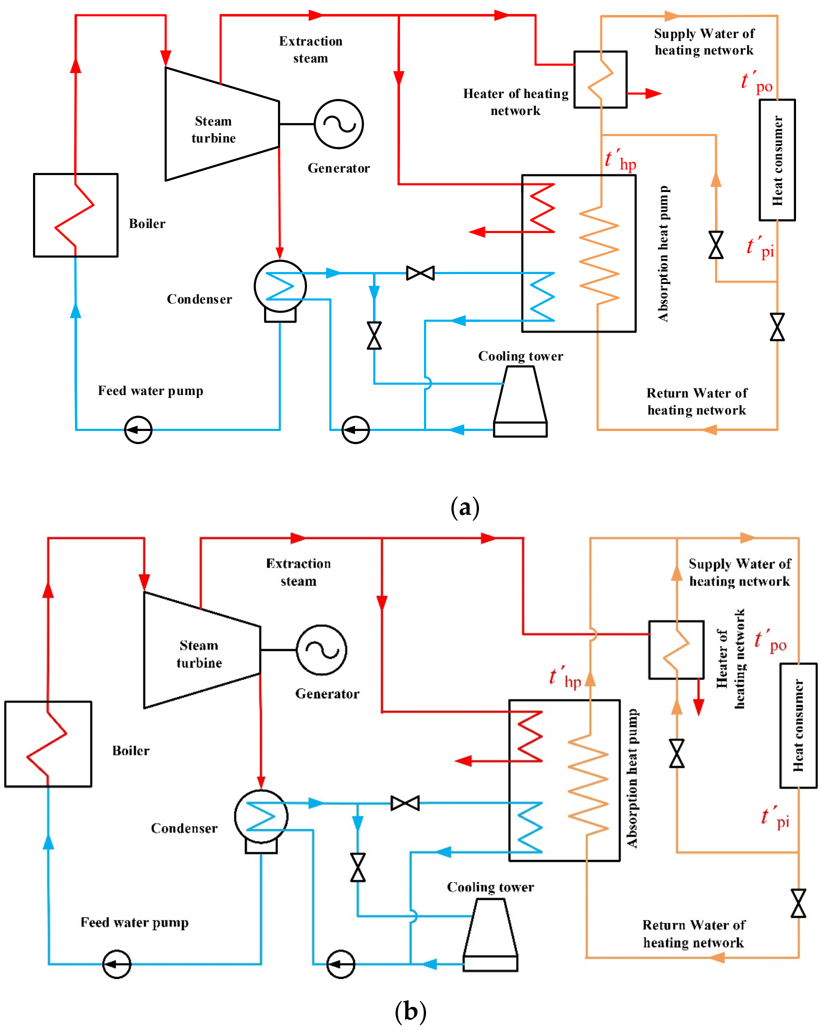

Figure 1. The heating supply system with the waste heat recovery system using an absorption heat pump: (**a**) series connection type, (**b**) parallel connection type.

2.2. Model of Heating Load Characteristics

The distribution characteristics of the heating load must be studied to realize on-demand heating and decrease heating energy consumption. In the actual central heating system, the heating load is affected by many factors, such as building types, meteorological conditions, and geographical locations. Among these factors, the temperature difference between indoors and outdoors has the greatest influence on the heating load. The actual heating load mainly depends on the outdoor temperature, because the indoor design temperature is fixed. In addition, different regions have different heating load characteristics. Heating load characteristics are usually expressed in the analytical formula of the heating load duration graph [28]. According to relevant regulations and standards of the heating industry, the following dimensionless formulas can be used to calculate the temperature distribution and heating load distribution during the heating period [28].

The actual outdoor temperature t_o can be expressed by Equation (1).

$$t_o = \begin{cases} t'_o & N \le 5 \\ t'_o + (5 - t'_o)R_m^b & 5 < N \le N_p \end{cases}, \tag{1}$$

where R_m, b, and μ are the dimensionless coefficients.

$$R_m = \frac{N-5}{N_p-5},\ \mu = \frac{N_p}{N_p-5},\ b = \frac{5-\mu\overline{t_o}}{\mu\overline{t_o}-t'_o},$$

where t'_o represents the outdoor design temperature during the heating period, $\overline{t_o}$ represents the average outdoor temperature during the entire heating period, N_p represents the average days of the heating period, and N represents the number of days for a certain outdoor temperature during the heating period.

Various losses in water transportation and heat exchange in the heating network are assumed to be negligible. From the user side, the water in the heating network is used to heat the indoor air to the indoor design temperature. According to the heat balance of the building, the heating load for a certain number of days can be described by Equation (2). When the actual outdoor temperature reaches the outdoor design temperature, the heat load reaches the maximum value. The maximum heating load can be calculated by Equation (3).

$$Q_h = K_1(t_i - t_o), \tag{2}$$

$$Q_m = K_1(t_i - t'_o), \tag{3}$$

where K_1 represents the characteristic coefficients relevant to the building heating, and t_i represents the design indoor temperature.

The relative heating load $\overline{Q_h}$, which is the ratio between the heating load for a certain number of days and the maximum heating load, can be calculated by Equation (4).

$$\overline{Q_h} = \frac{Q_h}{Q_m} = \frac{t_i - t_o}{t_i - t'_o}. \tag{4}$$

These parameters, including t'_o, $\overline{t_o}$, and N_p, are usually fixed values in a specific area and can be obtained from the local meteorological data. Design indoor temperature t_i is usually set as 18 °C in China. The heating load characteristic curve during the heating period in Figure 2 shows that the relative heating load is initially constant for 5 days and then decreases nearly linearly with the increase in duration.

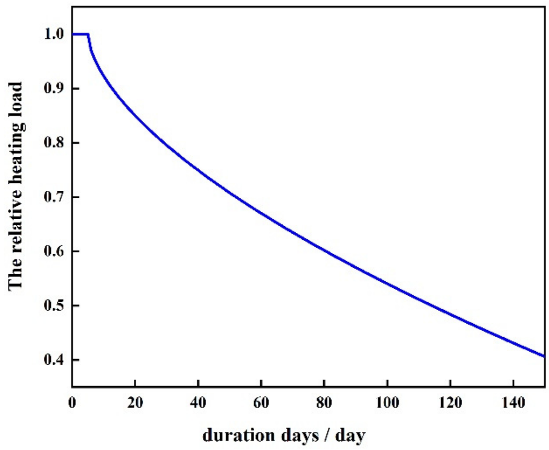

Figure 2. A typical characteristic curve of heating load.

Figure 2, also known as the heating load duration graph, shows the variation characteristic of the heating load of the heating network determined by the different outdoor temperature durations. The time interval of the heating load duration graph represents the whole heating period, and the abscissa start and end time of the heating load duration graph is not the actual heating start and end time, but the time of duration for a certain heating load which depends on the outdoor temperature. The initial time of the abscissa corresponds to the lowest outdoor temperature, and each time of the abscissa corresponds to an outdoor temperature. Each outdoor temperature lasts for a period of time. With the increase in the duration, the corresponding outdoor temperature gradually increases, so the heating load gradually decreases.

In addition, for the initial period of time, the time period in which the relative heating load curve remains parallel to the abscissa axis represents the time when the actual outdoor temperature is lower than the outdoor design temperature. This time represents the number of days for which the heating effect is not guaranteed, which is usually 5 days in China. At this time, the heating load reaches the maximum design heating load and remains unchanged.

2.3. Load Characteristic of Absorption Heat Pump in Heating Supply System

2.3.1. Model of Heating Network Regulation

In the actual operation of the heating network, the temperature or the flow rate of the supply and return water can be adjusted to meet the demands of the client. The water temperature control method, which is widely used in China, can be used to control the supply and return water temperature of the heating network and meet the heating load, while the water flow remains constant.

As the heating load mainly depends on heat consumers, the temperature of the supply and return water of the secondary heating network must be determined first to adjust the temperature of the supply and return water of the primary heating network. Under this temperature adjustment method, the supply and return water temperature of the secondary heating network can be calculated by Equations (5) and (6), respectively [27].

$$t_{so} = t_i + 0.5(t'_{so} + t'_{si} - 2t_i)\overline{Q}_h^{\frac{1}{1+b}} + 0.5(t'_{so} - t'_{si})\overline{Q}_h, \tag{5}$$

$$t_{si} = t_i + 0.5(t'_{so} + t'_{si} - 2t_i)\overline{Q}_h^{\frac{1}{1+b}} - 0.5(t'_{so} - t'_{si})\overline{Q}_h, \tag{6}$$

where t'_{so} and t'_{si} are the design supply and return water temperature of the secondary heating network, respectively, and b represents the index for the radiator.

For the primary heating network, the supply and return water temperature can be calculated by Equations (7) and (8), respectively.

$$t_{po} = \frac{[(t'_{po} - t'_{pi})\overline{Q}_h + t_{si}]e^{\frac{(t'_{po}-t'_{pi})-(t'_{so}-t'_{si})}{\Delta t'_p}} - t_{so}}{e^{\frac{(t'_{po}-t'_{pi})-(t'_{so}-t'_{si})}{\Delta t'_p}} - 1}, \tag{7}$$

$$t_{pi} = t_{po} - (t'_{po} - t'_{pi})\overline{Q}_h, \tag{8}$$

where $\Delta t'_p$ represents the logarithmic mean temperature difference between the primary and secondary heating network water under the design work condition.

$$\Delta t'_p = \frac{(t'_{po} - t'_{so}) - (t'_{pi} - t'_{si})}{\ln \frac{t'_{po}-t'_{so}}{t'_{pi}-t'_{si}}},$$

2.3.2. Load Characteristics of Heat Pump

t'_{po}, t'_{pi}, t'_{so}, and t'_{si} are usually determined during the design of the heating network. On the basis of Equations (7) and (8), the variation in the supply and return water temperature of the primary heating network and the outlet water temperature of the heat pump with the outdoor temperature are presented in Figure 3, where the temperature of supply and return water and the temperature difference between them gradually decrease with the increase in the outdoor temperature.

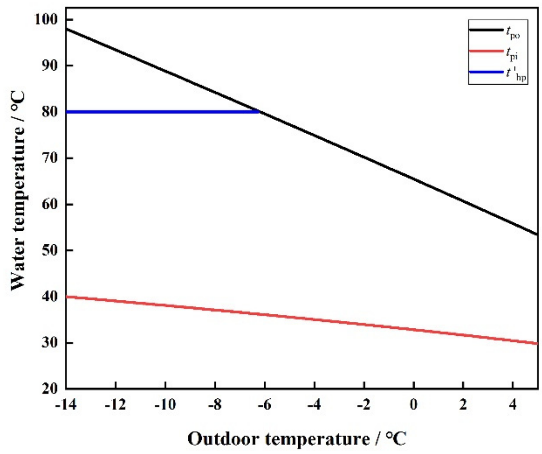

Figure 3. The temperatures of the supply water and return water vs. the outdoor temperature.

According to different application scenarios, various types of absorption heat pumps can be selected. In the waste heat recovery system, for the lithium bromide absorption heat pump which is widely used, its outlet water temperature is usually less than a specific value. When the outdoor temperature decreases, the supply water temperature of the heating network must be increased. However, when the supply water temperature is greater than the maximum outlet water temperature of the heat pump, the heat pump cannot satisfy the heating demand, such that the heater of the heating network must be put to use, as shown in Figure 1a.

When the outdoor temperature is lower than a specific value, the actual heating load of the heat pump with a fixed design power decreases with the decrease in the outdoor temperature. This is because the decrease in the outdoor temperature will increase the return water temperature of the heating network while the outlet water temperature of the heat pump remains constant. The maximum heating load of the heat pump could only be reached at point Y in Figure 4.

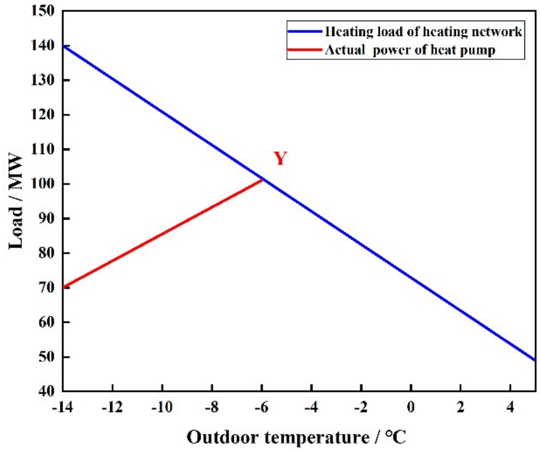

Figure 4. The relationship between the heating load and the outdoor temperature.

In an actual absorption heating system, if heat pumps with various design powers are used, the heat pumps will have different operating modes, and the load changes mainly manifest in four forms, as shown in Figure 5. In the following sections, P_d represents the design power characteristics of the heat pump, and P_X, P_Y, P_Z, and P_M represent the corresponding power of points X, Y, Z, and M in Figure 5.

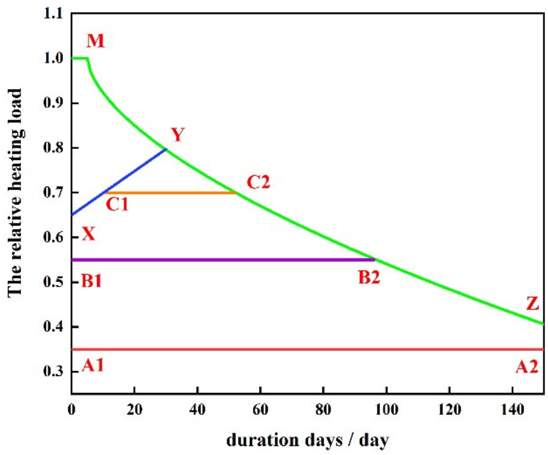

Figure 5. The operation mode of the heat pump in the waste heat recovery system.

1. When $P_d \leq P_Z$:

When the maximum outlet water temperature of the heat pump is lower than the minimum supply water temperature of the heating network, the heat pump could run at the design power throughout the entire heating period. The actual power curve of heat pump is shown as curve A1-A2 in Figure 5. Under the circumstances, a heater needs to be connected in series to further heat the outlet water of the heat pump, so as to meet the heating demand of the heat consumer. At this time, the configuration of the heating system is shown in Figure 1a.

2. When $P_Z < P_d \leq P_X$:

When the outdoor temperature is low, the heat pump could run at the design power. When the outdoor temperature is high, the heat pump will be limited by the heating load of the heating network. The actual power curve of heat pump is shown as curve B1-B2-Z in Figure 5. In the B1-B2 section of the heat pump load curve, $t'_{hp} < t'_{po}$, and the heating supply system that connects the absorption heat pump and the heater in series can meet the heating demand, as shown in Figure 1a. In the B2-Z section of the heat pump load curve, $t'_{hp} \geq t'_{po}$, the heater can be stopped at this time, and the outlet water of the heat pump can be directly used as the supply water of the heating network.

3. When $P_X < P_d < P_Y$:

Under the condition of low outdoor temperature, the heat pump is limited by its own performance. When the outdoor temperature is high, the heat pump will be limited by the heating load of the heating network. Therefore, it could only run at design power within a part of the outdoor temperature range. The actual power curve of the heat pump is shown as curve X-C1-C2-Z in Figure 5. In the X-C1-C2 section of the heat pump load curve, the heating supply system that connects the absorption heat pump and the heater in series can meet the heating demand, as shown in Figure 1a. Just like the curve B2-Z, in the C2-Z section of heat pump load curve, the outlet water of the heat pump can be directly used as the supply water of the heating network.

4. When $P_d = P_Y$:

When the outdoor temperature is low, limited by its own performance, the actual thermal load of the heat pump cannot reach the design power. When the outdoor temperature is high, the heat pump will be limited by the heating load of the heating network. Therefore, it could only run at the design power at point Y, and the actual power curve of heat pump is shown as curve X-Y-Z in Figure 5. In the X-Y section of heat pump load curve, the heating supply system that connects the absorption heat pump and the heater in series can meet the heating demand, as shown in Figure 1a. Just like the curve C2-Z, in the Y-Z section of heat pump load curve, the outlet water of the heat pump can be directly used as the supply water of the heating network.

Furthermore, it is assumed that the maximum heating load of the heating supply system without the heat pump is P_0, then the relationship between P_X, P_Y, P_Z, and P_0 is as follows.

$$P_Z = \overline{Q}_{h,r}\left(P_0 + \frac{COP - 1}{COP} P_Z\right), \tag{9}$$

$$P_X = \frac{t'_{hp} - t'_{pi}}{t'_{po} - t'_{pi}}\left(P_0 + \frac{COP - 1}{COP} P_X\right), \tag{10}$$

$$P_Y = \frac{t'_{hp} - t^Y_{pi}}{t'_{hp} - t'_{pi}} P_X, \tag{11}$$

where $\overline{Q}_{h,r}$ represents the ratio between the minimum and maximum heating load during the heating period, t^Y_{pi} represents the return water temperature at point Y, and COP represents the coefficient of the performance of the heat pump.

When the design supply water temperature is not larger than the outlet water temperature of the heat pump, the system is shown as Figure 1b. When the outdoor temperature is low, the heat pump is not limited by its power curve, but will only be limited by the heating load when the outdoor temperature is high. Thus, its operation mode will be curve A1-A2 or curve B1-B2-Z in Figure 5. In addition, for a certain unit the relationship of the heating power from the extraction steam and the exhaust steam should also be considered so as to analyze whether all the waste heat can be completely recovered.

During the heating period, the supplied heating quantity provided by the heat pump can be expressed by the area surrounded by the heat pump load curve, as shown in Figure 5. Based on the above discussion, the relationship between the supplied heating quantity provided by the heat pump and the design power of the heat pump is obtained, as shown in Figure 6. It is worth noting that, during the whole heating period, as the design power of the heat pump increases the heating supply of the heat pump increases first and then tends to be constant.

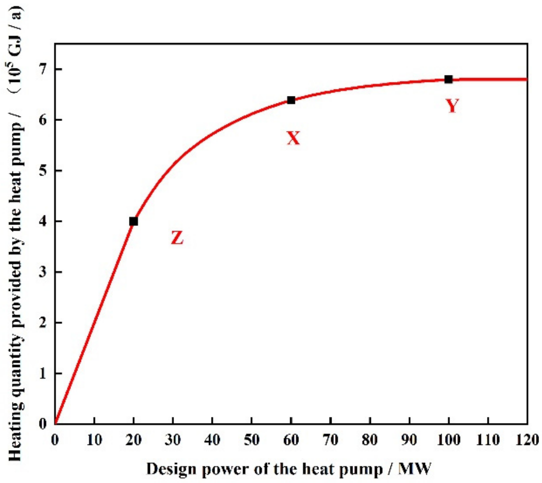

Figure 6. The supplied heating quantity of the heat pump with different design power during the heating period per year.

When the COP of the heat pump remains constant, the income of the heat pump depends on the waste heat quantity recovered by the heat pump. For different design powers of the heat pump, the operation mode of the heat pump and the recovered exhaust heat quantity vary. Moreover, the initial investment of the waste heat recovery system depends on the heat pump power. Thus, the appropriate heat pump design power should be selected to achieve the best economy of the system.

3. Economic Analysis Model of the Waste Heat Recovery System

In the waste heat recovery system, the power of the heat pump is an optional parameter which will affect the economy of the system. In this section, an economic analysis model of the system is proposed to calculate the economy of the system and obtain an optional power of the heat pump based on the constant electricity power.

The cost of the waste heat recovery system mainly consists of the operating cost and the initial investment. The design power of the heat pump determines the initial investment which can be calculated by Equation (12). In China, the energy reconstruction project usually adopts the energy performance contracting style, and most of the initial investment, such as 80%, is from the bank. The bank loan can be expressed by Equation (13).

$$I_i = P_d \times r_p, \tag{12}$$

$$I_{bl} = I_i \times x, \tag{13}$$

where r_p is the unit price of the recovery system using the absorption heat pump; x represents the lending ratio of the initial investment from the bank.

The operating cost of the system includes the cost of the principal, the interest, the electricity consumption, the salary of the workers, and other costs. Adopting the constant payment mortgage method, the principal and the interest for each year can be calculated by Equation (14). The cost of electricity consumption and the salary of the workers can be calculated by Equations (15) and (16), respectively.

$$I_{pi} = 12 \times \left[\frac{P_d \times r_p \times x \times \frac{i}{12} \times (1 + \frac{i}{12})^{12n}}{(1 + \frac{i}{12})^{12n} - 1} \right], \tag{14}$$

$$I_e = P_d \times r_e, \tag{15}$$

$$I_s = m \times r_s, \tag{16}$$

where n is the payback period of the bank loan, i is the loan interest rate per year, r_e is the electricity consumption of the system per each MW heat pump, m is the number of the works for the system, and r_s is the salary of each worker.

The other cost is usually 4% of the sum total of I_{pi}, I_e, and I_s.

From Section 2, the heating load characteristic for the heating supply system is obtained, as can be seen from Figure 7. For a heat pump with a fixed design power, its actual operating load $P_{hp}(t)$ can be represented by the actual power curve of the heat pump and the heating load of the heating network. During the whole heating period, the waste heat recovered by heat pump can be expressed by Equation (17). The increased heating quantity Q_i can be expressed by Equation (18).

$$Q_{whp} = \int_0^{N_P} P_{hp}(t)(1 - \frac{1}{COP})dt, \tag{17}$$

$$Q_i = \int_0^{N_P} \overline{Q}_h P_{di} dt, \tag{18}$$

where P_{di} represents the increased heating load at the design heat pump power.

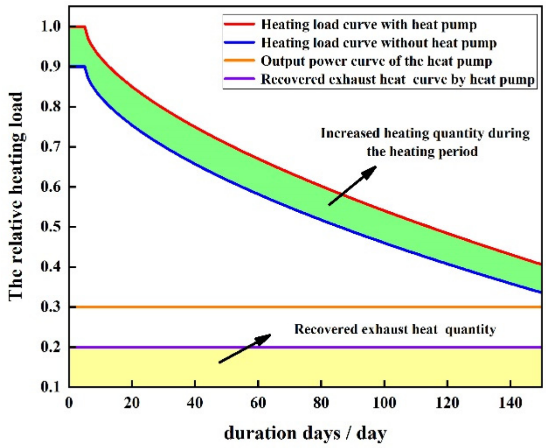

Figure 7. The heating load characteristic for the heating supply system.

In fact, Q_{whp} is invariably greater than Q_i, which shows that the waste heat recovered by the heat pump is used not only for heating but also for electricity power generation. The recovery of waste heat lowers the amount of steam extraction during power generation, thereby reducing coal consumption. The energy consumption reduced by saving coal can be calculated by Equation (19).

$$Q_s = Q_{whp} - Q_i. \tag{19}$$

Then, the coal savings of the cogeneration unit can be expressed by Equation (20).

$$B_s = \frac{Q_s}{\eta_p \eta_b q_l}, \tag{20}$$

where η_p and η_b represent the pipe efficiency and boiler efficiency, respectively; q_l represents the net calorific power of coal.

The total income from the waste heat recovery system can be calculated by Equation (21).

$$I_0 = I_t + I_b = r_t Q_i + r_b B_s, \tag{21}$$

where I_t is the income brought by the increased heating quantity, I_b is the revenue from coal saving during power generation, r_t represents the heating price, and r_b represents the price of the standard coal.

The annual after-tax profit of the system and the rate of return on the initial investment can be calculated by Equations (22) and (23), respectively.

$$I_p = (1 - IT)(I_0 - I_c), \tag{22}$$

$$ROI = I_p / I_i, \tag{23}$$

where I_c is the total cost of the waste heat recovery system per year, I_i represents the initial investment, and IT represents the income tax rate.

From the above model, I_p or ROI under the different design power of the heat pump can be obtained, and then the appropriate design power of heat pump can be achieved.

4. Case Study

A typical unit CZK135/112-13.2/0.245/535/535 is considered to use the heat pump to recover the waste heat from a low-grade steam turbine exhaust for heating. The unit is an ultra-pressure bleeder turbine with a single reheat. It has two heating extraction steams, one for industrial heating supply from the intermediate pressure stage and another for building heating supply from the exhaust steam of the intermediate pressure stage. The detailed thermal parameters of the unit are shown in Table 1.

Table 1. Detailed thermal parameters of the case unit.

No.	Parameters	Unit	Value
1	Main steam flow	t/h	480
2	Heating-extracting steam flow	t/h	150
3	Available exhausted steam flow	t/h	202.266
4	Exhaust steam pressure	MPa	0.015
5	Power generation	MW	130.159
6	Backwater temperature	°C	104
7	Boiler efficiency	%	92
8	Pipe efficiency	%	99
9	Mechanical efficiency	%	99
10	Generator efficiency	%	98.5

For the unit, the heat recovery system of turbine exhaust steam using an absorption heat pump for heating supply based on heating load characteristics is designed. The main original data for the design are listed in Table 2.

Table 2. The main original data for the system design.

No.	Items	Units	Values
1	Calculated outdoor temperature for heating	°C	−14
2	Days of the heating period	d/yr	150
3	Price of the standard coal	RMB/t	400
4	Price of the electricity	RMB/kWh	0.43
5	Price of the heating	RMB/GJ	35.48
6	COP of heat pump		1.7
7	Unit price of the recovery system using absorption heat pump	RMB/MW	20,0000
8	Electrical load consumed by heat pump system per MW	kW/MW	4
9	The salary of the workers	RMB	50,000 × 8
10	The lending ratio of the initial investment from the bank	%	80
11	The payback period of the bank loan	y	10
12	The loan interest rate per year	%	7.05
13	The income tax	%	25
14	The temperatures of the supply water	°C	98
15	The temperatures of the backwater	°C	40
16	Maximum outlet water temperature of the heat pump	°C	80

4.1. Optimization of the Design Power of the Heat Pump

Figures 8 and 9 show I_p and *ROI* at different design powers of the heat pump. It can be seen from Figures 8 and 9, when the design power of the heat pump are 101.0 and 80.0 MW, I_p and *ROI* reach the maximum value, respectively. The optimal design power of the heat pump for this unit is 101.0 or 80.0 MW, according to different economic indices. The maximum value of I_p is 828.1×10^4 RMB, while the maximum value of *ROI* is 41.1%.

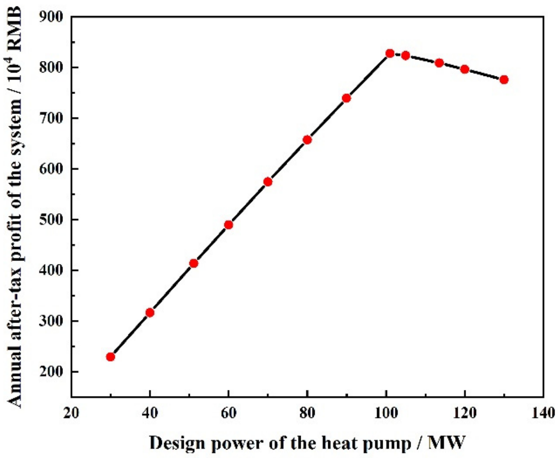

Figure 8. I_p at different design powers of the heat pump.

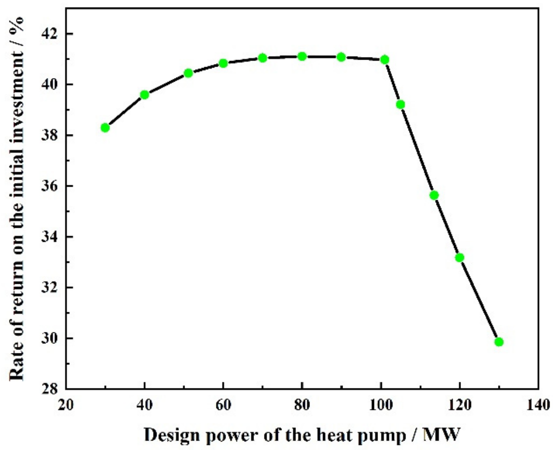

Figure 9. *ROI* at different design powers of the heat pump.

Although the maximum value of *ROI* appears when the design power of the heat pump is 101.0 MW, the decrement in *ROI* is small when the design power is in the range of 50 to 101.0 MW. If only focusing on *ROI*, the smaller design power of the heat pump is also appropriate.

4.2. Economic Analysis of Waste Heat Recovery System Using Absorption Heat Pump

According to the economic model in Section 3, the unit price of the heat pump recovery system and the prices of the standard coal, the heating, and the electricity will all impact the economy of the waste heat recovery system. The economy of the system also varies with the changes in these influencing factors in market value.

4.2.1. Effect of Unit Price of the Recovery System

The effect of the unit price of the recovery system using an absorption heat pump on the economy of the system is presented in Figures 10 and 11, including two optimal design powers of the heat pump. The figures show that the unit price of the recovery system using an absorption heat pump substantially affects the economics of the system.

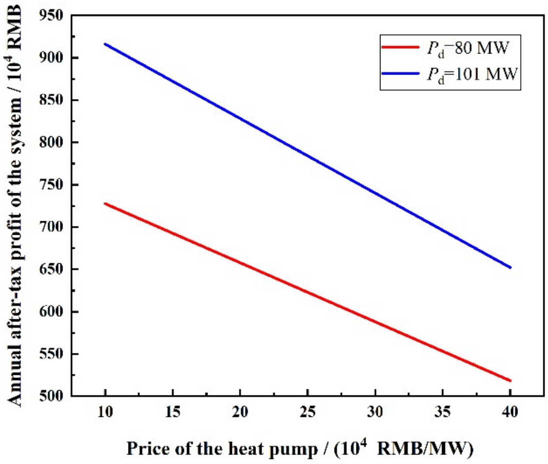

Figure 10. Annual after-tax profits vs. uthe nit price of the recovery system using an absorption heat pump.

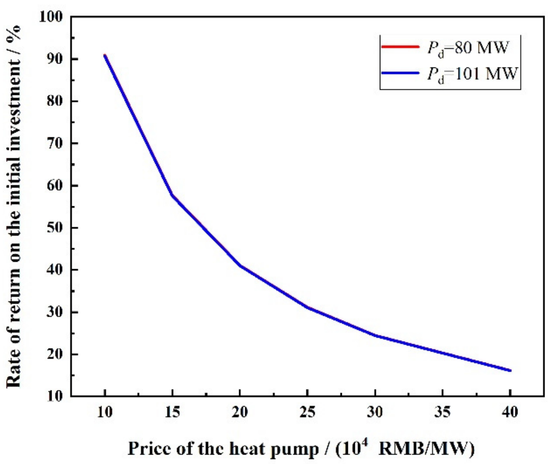

Figure 11. Rate of return on initial investment vs. the unit price of the recovery system using an absorption heat pump.

When the unit price changes from 10×10^4 to 40×10^4 RMB/MW, the annual after-tax profit decreases from 910×10^4 to 652×10^4 RMB in the case of a 101.0 MW design power and from 727×10^4 to 518×10^4 RMB in the case of an 80.0 MW design power. Compared with the current design price, the relative variation ranges are from +10.6% to −27.0% and from +10.6% to −21.2%. For the rate of return on initial investment, it is very close to each other for the two optimal design powers and changes from 90% to 20%, and the relative variation range is from +121.2% to −60.6%.

4.2.2. Effect of Standard Coal Price

The effect of the standard coal price on the economy of the system is presented in Figures 12 and 13. When the price of the standard coal changes from 200 to 800 RMB/t, the annual after-tax profit increases linearly, and the increment is about 60×10^4 RMB for the two optimal design powers. For the rate of return on initial investment, it varies nearly linearly from 39.9% to 43.0% in the case of a 101.0 MW design power, and from 40.0% to 43.6% in the case of an 80.0 MW design power.

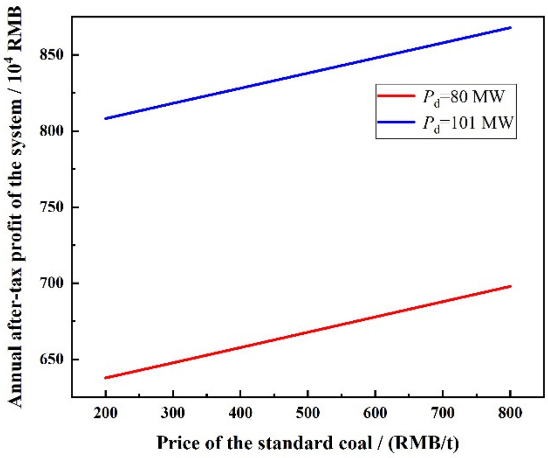

Figure 12. Annual after-tax profits vs. the price of the standard coal.

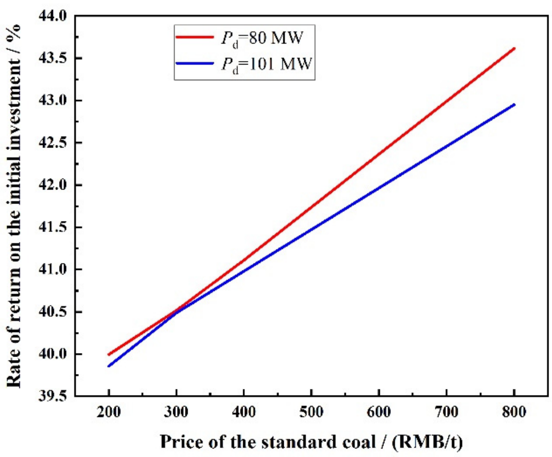

Figure 13. Rate of return on initial investment vs. the price of the standard coal.

4.2.3. Effect of Heating Price

Figure 14 shows the annual after-tax profits of the system with different heating prices. When the heating price changes from 20 to 40 RMB/GJ, the annual after-tax profit of the system increases from 382×10^4 to 1535×10^4 RMB in the case of a 101.0 MW design power and from 304×10^4 to 1217×10^4 RMB in the case of an 80.0 MW design power. Figure 15 shows the *ROI* with different heating prices. When the heating price changes from 20 to 40 RMB/GJ, for the two optimal design powers the rates of return on the initial investment are close to each other and vary from 19.0% to 76.0%. Compared with the current design price, the relative variation range is from −53.8% to +85.2%. The results show that the heating price is another substantial influencing factor on the economy of the waste heat recovery system.

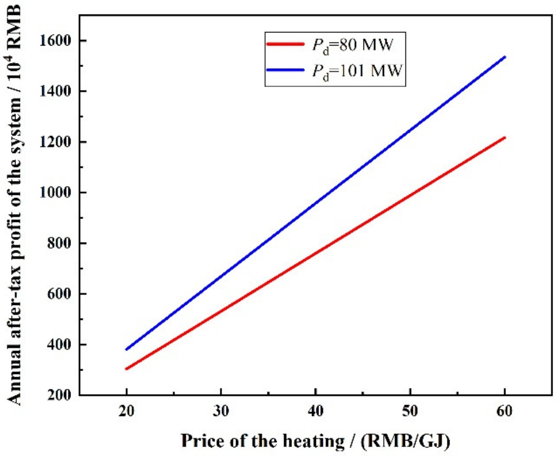

Figure 14. Annual after-tax profits vs. the price of heating.

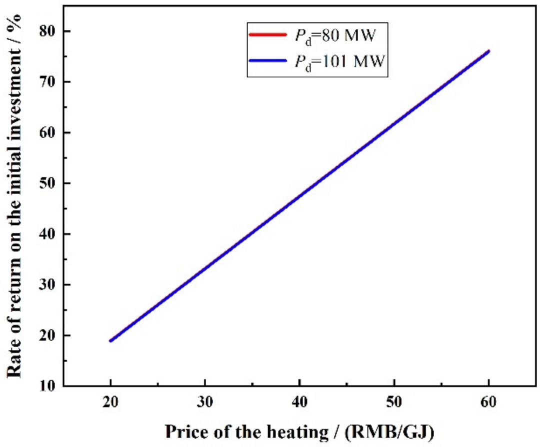

Figure 15. Rate of return on the initial investment vs. the price of heating.

4.2.4. Effect of Electricity Price

Figure 16 shows the annual after-tax profits of the system with different electricity prices. When the heating price changes from 0.2 to 0.6 RMB/kWh, the annual after-tax profit of the system decreases by about 20 × 10^4 RMB for the two optimal design powers. Figure 17 shows the rate of return on the initial investment with different electricity prices. When the heating price changes from 0.2 to 0.6 RMB/kWh, the rate of return on the initial investment varies from 41.8% to 40.5%. The results show that the effect of the electricity price on the economy of the system is small.

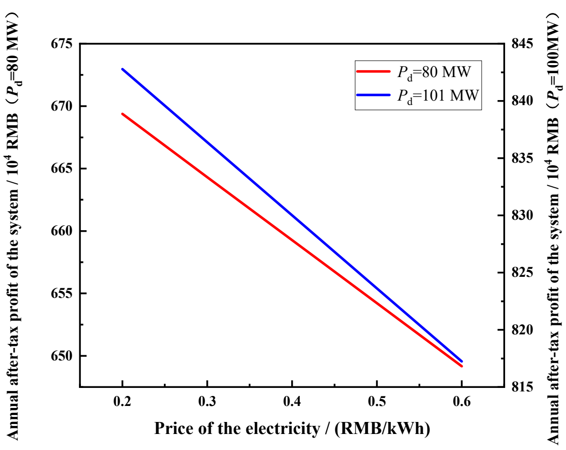

Figure 16. Annual after-tax profits vs. the price of the electricity.

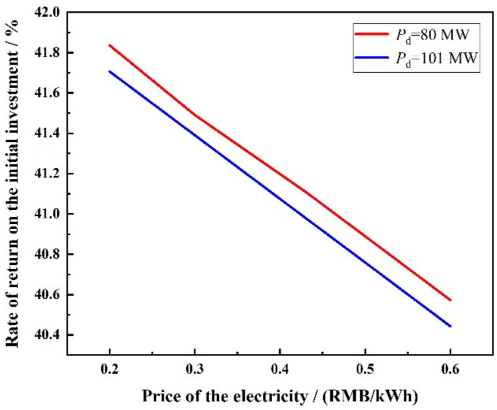

Figure 17. Rate of return on the initial investment vs. the price of the electricity.

5. Conclusions

On the basis of heating load characteristics, the design idea of a waste heat recovery system with a heat pump was presented in this paper. In order to satisfy the heating demand of different temperature levels, two connection types of heating supply systems were proposed. According to the relationship between the heating network load and the design power of the heat pump, four operating modes of the heat pump were discussed. An economic analysis model of the waste heat recovery system was proposed to optimize the design power of the heat pump. Finally, a detailed quantitative economic analysis of the waste heat recovery system is carried out with a typical unit. The main conclusions are summarized as follows:

- Throughout the heating period, with the change in the outdoor temperature, changes in the heating load of the heating network will affect the actual output power of the heat pump with a determined design power. As the outdoor temperature increases, the actual output power of the heat pump first increases and then decreases, reaching the maximum value at a certain outdoor temperature in the middle.
- As the heating load of the heating network is constantly changing during the heating period, the actual output power characteristics of heat pumps with different design powers are quite different, which causes the waste heat recovery system to operate at different modes. When the design power of the heat pump is lower than the minimum load of the heating network, the heat pump can always operate at the design power. However, when the design power of the heat pump is higher than the minimum load of the heating network, the heat pump can only operate under partial load in certain periods. Therefore, the reasonable selection of the design power heat pump is crucial to improve the economy of the waste heat recovery system.
- The economic analysis of a 135 MW unit shows that the key parameters affecting the efficiency of the waste heat recovery system are the unit price of the recovery system and the heating price. Under the condition that the design power of the heat pump is 101.0 MW, when the unit price changes from 10×10^4 to 40×10^4 RMB/MW, the annual after-tax profit decreases from 910×10^4 to 652×10^4 RMB and the rate of return on the initial investment decreases from 90% to 20%. When the heating price changes from 20 to 40 RMB/GJ, the annual after-tax profit of the system increases from 382×10^4 to 1535×10^4 RMB and the rate of return on the initial investment increases from 19.0% to 76.0%. Therefore, a lower unit price of the recovery system or a higher heating price would considerably increase the efficiency of the system.

In northern China, the combined heat and power plant is usually applied for urban heating, and is located in the place around heat consumers. The operation model of the cogeneration unit adopts the following heating load mode, which means that the unit gives priority to the heating load and the amount of electricity is determined by the heating load. When the heating load changes, the electricity generation capacity of the thermal power plant changes accordingly. As we know, due to the differences in population, climate, industrialization level, and other aspects of different regions, the heat and electricity consumption in each region is also different. When the cogeneration unit is used to provide heat and electricity for a certain area, the population and industrialization level of the area should be considered comprehensively. In an area dominated by residential users, more consideration should be given to meet the heating demand. In this case, the electricity generation is usually higher than the electricity consumption of residents in the area, so the remaining electricity can be considered to upload to the power grid to meet the electricity demand of other regions. In an area dominated by industrial users, then the electricity demand usually exceeds the heating demand. The electricity generated by the cogeneration unit cannot meet the electricity demand in the region, so additional electricity needs to be obtained from the power grid. Therefore, it is necessary to reasonably allocate the proportion of heat and electricity according to the actual situation for each region.

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Nomenclature

B_s	the coal saving in electricity generation
COP	the coefficient of performance of the heat pump
IT	the income tax rate.
I_0	the total income from the waste heat recovery system
I_b	the income from coal saving in electricity generation
I_{bl}	the bank loan
I_e	the cost of electricity consumption
I_t	the income from increased heating quantity
I_i	the initial investment
I_p	the annual after-tax profit of the system
I_{pi}	the principal and the interest for each year
I_s	the salary of the workers
i	the loan interest rate per year
K_1,K_2	the characteristic coefficients relevant to the building heating
m	the number of the works for the system
n	the payback period of the bank loan
N	the number of days for a certain outdoor temperature during the heating period
N_p	the days of the heating period
P_d	the design power of heat pump
P_X,P_Y,P_Z	the design power of the heat pump at points X, Y, and Z, respectively
$P_{hp}(t)$	the actual operating load of the heat pump
P_{di}	the increased heating load at the design heat pump power
Q_h	the heating load for a certain number of days
Q_m	the maximum heating load during the heating period
Q_s	the energy corresponding to the coal saving
Q_{whp}	the recovered waste heat quantity during the heating period
Q_i	the increased heating quantity during the heating period
$\overline{Q}_h$	the heating load coefficient
$\overline{Q}_{h,r}$	the ratio between the minimum and maximum heating load during the heating period

r_b	the price of standard coal
r_e	the electricity consumption of the system per MW heat pump
r_p	the unit price of the recovery system using absorption heat pump
r_s	the salary of each worker
r_t	the heating price
ROI	the rate of return on the initial investment
t_i	the design indoor temperature
t'_{hp}	the maximum value of the outlet water temperature of the heat pump
t'_o	the calculated outdoor temperature during the heating period
t_o	the outdoor temperature
$\overline{t_o}$	the average outdoor temperature during the heating period
t'_{po}	the design supply water temperature of primary heating network
t_{po}	the supply water temperature of primary heating network
t'_{pi}	the design return water temperature of primary heating network
t_{pi}	the return water temperature of primary heating network
t_{so}	the supply water temperature of secondary heating network
t_{si}	the return water temperature of secondary heating network
t_{pi}^{Y}	the return water temperature of primary heating network at point Y
x	the lending ratio of the initial investment from the bank
Greek symbol	
η_p	the pipe efficiency
η_b	the boiler efficiency

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