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Performance study of a dual-loop booster heat pump in the deep recovery of boiler flue gas waste heat

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Abstract

Traditional district heating systems face disadvantages such as low utilization of renewable energy and high system heat loss, while ultra-low temperature district heating (ULTDH) systems can make full use of low-temperature waste heat or renewable heat sources while reducing the heat loss of the pipe network. To deeply recover the low-temperature waste heat from the flue gas of a gas boiler in a heating project in Beijing, this paper designs a dual-loop booster heat pump system and uses it in the ULTDH system. The coefficient of performance (COP) and annual power consumption of the designed booster heat pump operating in the ULTDH system is simulated and analyzed using DeST software and actual compressor specifications. The results show that the average COP of the dual-loop booster heat pump is 0.92 higher than that of the conventional heat pump, which can save about 0.034 million kW·h of electrical energy during the heating period, and has a large energy-saving potential and broad market prospect.

Keywords: Booster heat pump; ultra-low temperature district heating; deep flue gas heat recovery.

1. Background

Current energy systems worldwide consume vast amounts of energy, even triggering global climate change. To achieve sustainable development strategies, there is a need to reduce primary energy consumption and gradually transition to sustainable energy. Among all energy consumption, building energy consumption account for a huge proportion of energy consumption, so improving building energy consumption is an effective way to achieve efficient energy use[1-3]. Currently, the district heating of buildings in China is still dominated by coal-fired and gas-fired boilers, which pollutes the atmospheric environment and brings the problem of excessive energy utilization. Therefore, the effective recovery of low-grade waste heat or using renewable energy for building heating and hot water is an effective way to reduce energy consumption and achieve sustainable development[4-6].

In recent years, researchers have proposed an ultra-low temperature district heating system (ULTDH) that can fully use low-temperature heat sources or renewable energy, also known as the fifth generation district heating system. ULTDH improves the problems of significant heat loss, high energy consumption and less available heat sources in traditional district heating networks. The water temperature flowing from the heating network of the ULTDH is lower than 50 °C, even as low as 25 °C[7,8]. Since the hot water temperature of the ultra-low temperature district heating system is relatively low, the hot water should be heated by the heat pump (booster heat pump) before passing through the terminal equipment to meet the requirements of the user or terminal equipment. In this case, the heat loss can be minimized to the extent that no pipe insulation is required because the hot water is close to the ambient temperature as it flows through the pipe network[9-14].

The high-temperature flue gas emitted from conventional district heating boilers can be recovered and utilized by heat exchangers or absorption heat pumps. But in the low-temperature flue gas still contains a large amount of waste heat that can be used. The compression heat pump can deeply recover the low-temperature

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flue gas waste heat between 30~60℃[15-18]. Mu et al.[19] applied heat pumps to flue gas recovery and conducted an experimental analysis of the performance of heat pumps. Compared with the energy consumption of gas boilers, exhaust-source heat pumps can save 55% of standard coal. The comprehensive energy efficiency ratio of heat pumps can reach more than 4.0. However, because two sets of units are needed to supply heat and domestic hot water separately, there are problems with occupying large space and large installation and operation and maintenance costs. Wu et al.[20] analyzed the engineering application of exhaust-source heat pumps. The results show that although the traditional heat pump has greater advantages in waste heat utilization, the large-scale implementation of the application is more difficult due to the large number of equipment and complex system operation. Huang et al.[21] address the problem of low utilization of waste heat from flue gas boilers, combined with air source heat pump technology for low-level flue gas waste heat for gradient depth recovery and utilization. Results show that by recycling flue gas waste heat, with low valley electricity prices, the heating cost of domestic hot water can be reduced more significantly, with energy saving, emission reduction, water saving and other economic benefits. However, the initial investment cost of the system is large. In the face of large temperature differences, there are still problems of relatively low energy efficiency and poor system heat transfer efficiency.

Due to the problems of high initial investment cost, large floor space and low heat transfer efficiency of the system under large temperature difference conditions, this paper designs a dual-loop heat pump system for boiler flue gas deep recovery. Integrating two independent heat pump loops into one device improves the uniformity of the heat transfer process and the coefficient of performance (COP) of the heat pump. The dual-loop booster heat pump is applied to the deep recovery of boiler flue gas waste heat in a district heating project in Beijing. Based on the performance of the actual compressor, the operating performance of this dual-loop booster heat pump was simulated and analyzed using DeST software.

2. System design and application scheme

2.1. Dual-loop booster heat pump system

The flue gas waste heat recovery device integrated with the heat pump is shown in Fig. 1. Firstly, the boiler flue gas and part of the heating return water for heat exchange, then the flue gas is discharged to the flue gas heat exchanger, in the flue gas heat exchanger for intermediate water heating, flue gas reduced to a certain temperature and then discharged to the heat exchanger, the heated intermediate water as a low-temperature heat source into the heat pump, the heat pump will be the remaining heat network return water heated to the heating temperature.

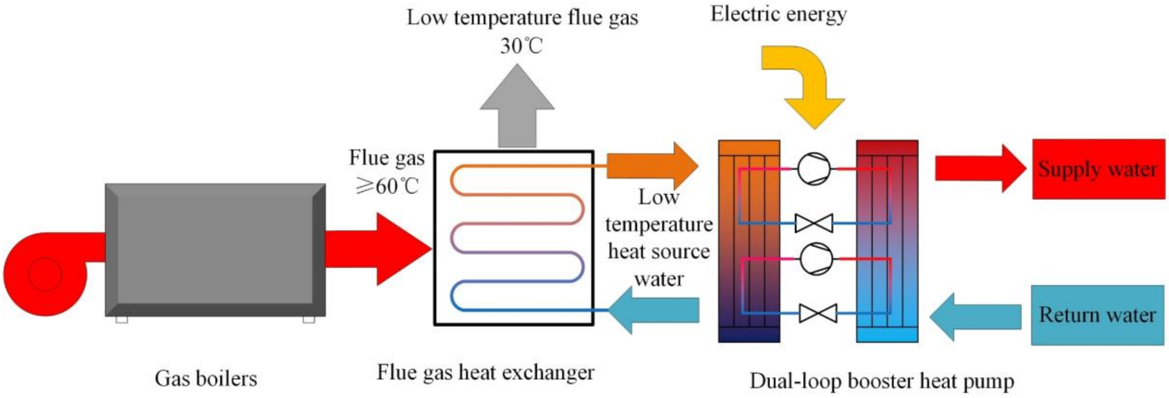


Fig. 1. Combined utilization of flue gas waste heat recovery device and booster heat pump.

Fig. 2(a) shows the designed new dual-loop heat pump system. After absorbing the flue gas waste heat, the hot intermediate water enters the evaporator of the heat pump to exchange heat with the refrigerant, the booster heat pump absorbs heat from the intermediate water and raises the refrigerant to a higher temperature with the input of electrical energy to heat the heating return water in the condenser. The designed dual-loop system contains two compressors, two expansion valves, an evaporator and a condenser. The return water enters from the inlet of the condenser and carries out counter-current heat exchange with the refrigerant in the low-temperature loop and the high-temperature loop successively, and then discharges from the outlet of the condenser after reaching the required temperature of the user and flows to the user side for heating; the heat source water enters from the inlet of the evaporator and carries out counter-current heat exchange with the refrigerant in the high-temperature loop and the low-temperature loop successively. The pressure-enthalpy diagram of the dual-loop heat pump system is shown in Fig. 2(b), where cycle 1-2-3-4-1 represents the low-temperature loop and cycle 5-6-7-8-5 for the high-temperature loop.

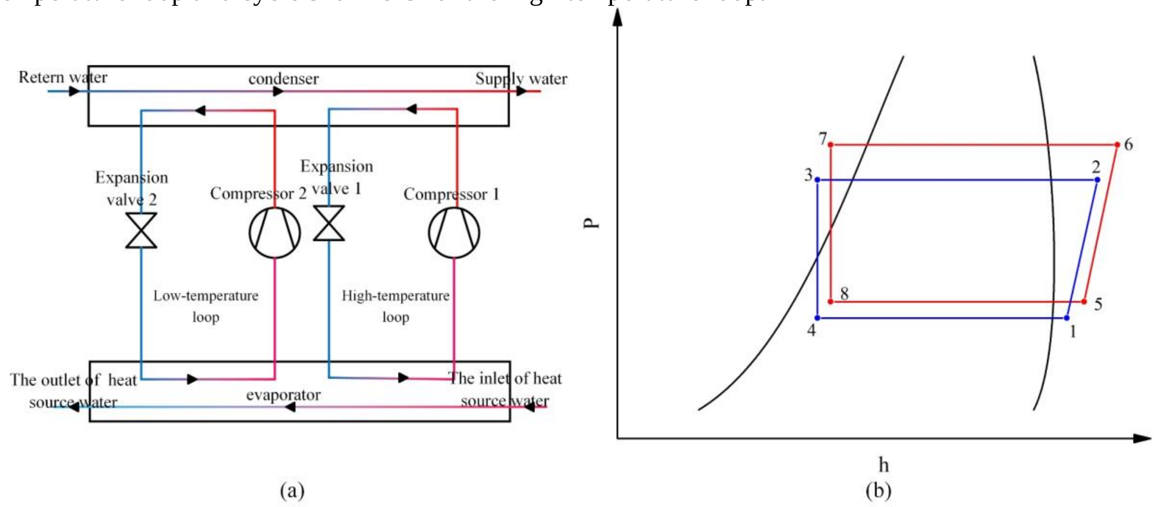


Fig. 2. (a) Schematic of the dual-loop system; (b) P-h diagram of dual-loop heat pump system.

2.2. Application scheme

This paper designs a traditional single-loop and a new dual-loop booster heat pump for flue gas waste heat recovery in a heating boiler room in Beijing, and the heat recovered by the booster heat pump heat some commercial buildings in the area, and this boiler room is divided into two rooms in the North and South, covering 188,848 m² and 353,603 m², respectively, the design indexes are shown in Table 1.

Table 1. Waste heat recovery indexes

Building location	Heating load for commercial (*kW*)	Heating load for residential (*kW*)	Total heating load (*kW*)	Index of waste heat recovery (*kW*)
South area	8498.19	893.82	9392.02	470
North area	15912.15	957.83	16869.99	843.5

The main heating form of the project is gas boiler heating, and the flue gas is the main waste heat source of the project itself. The waste heat recovery index is 5% of the total heat load, the total installed capacity of the South area is 9392kW, and the total installed capacity of the North area is 16870kW. The waste heat recovery index of the heat pump in the South area is 470kW, and the waste heat recovery index of the heat pump in the North area is 843.5kW. The heat recovered from the heat pump will be used to meet the heat demand of some buildings in the area, the main load of this part of the building is commercial heat load, mainly concentrated during the daytime, with insulation running at night.

For the traditional single-loop booster heat pump systems, each unit is set to have a rated heat capacity of 150kW. For the new dual-loop booster heat pump systems, each unit is set to have a rated heat capacity of 240kW, and the heat production is made to meet the heat load requirements by connecting multiple units in parallel. For the South area, the index of waste heat recovery is 470kW, so the single-loop heat pump in the South area is set to 4 units in parallel, and the dual-loop heat pump is set to 2 units in parallel. In the North area, the waste heat recovery index is 843.5kW, so the single-loop system in the North area is set to 6 units in parallel, and the dual-loop heat pump is set to 4 units in parallel.

Due to the large amount of low-temperature flue gas discharged from the district heating boiler, it is necessary to select a large-capacity compressor that can operate at low-temperature conditions. According to the compressor's applicable temperature range and heat capacity, the working fluid's safety and economy. Danfoss DSH381-4 scroll compressor and R410A are selected, and the curve of COP with temperature is shown in Fig. 3.

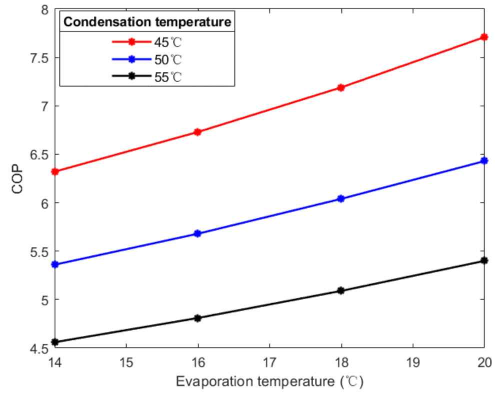
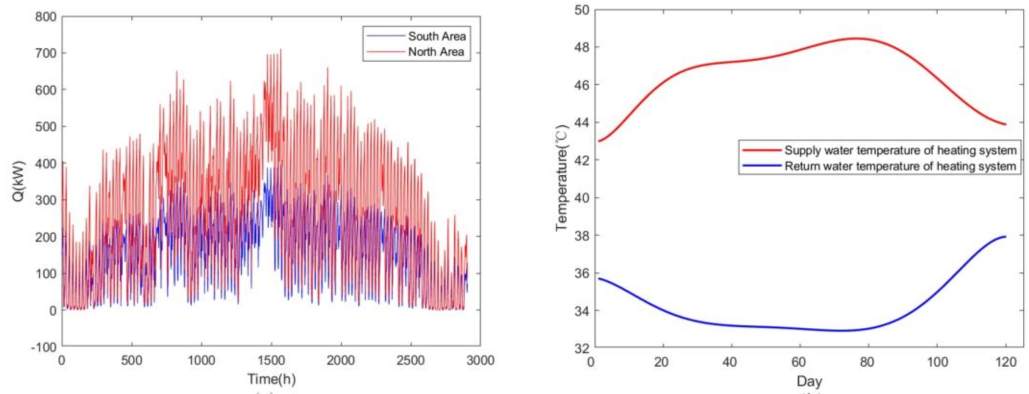


Fig. 3. Danfoss DSH381-4 Compressor Performance Curve.

2.3. The curve of the heating load

In this case, the heat recovered from waste heat is used for heating some buildings in this area. To meet the real-time heat demand of users, this paper has used DeST software to conduct modeling and simulation and obtains the hourly heating load curve of the whole heating period of some buildings in this area. As shown in Fig. 4(a), the heating period is from November 15 to March 15 of the following year, totaling 2904 hours. In Fig. 4, the horizontal coordinate represents the time and the vertical coordinate represents the heating load, the blue curve is the heating load of some buildings in the North area and the red curve is the heating load of some buildings in the South area. The average hourly heating load of the buildings in the North area is 261.76kW, and the maximum heating load can be 710.75kW, while the average hourly heating load of the buildings in the South area is 145.75kW, and the maximum heating load is 395.74kW, the waste heat recovery index can fully meet the heating load demand of this part of the buildings. From the perspective of the whole heating period, the overall trend of hourly heating load in both the South and North areas is first increased and then decreased, which is consistent with the actual local climate change. It is shown in Fig.4 (a) that the heating load fluctuates greatly in a short time interval, this is because the buildings are mainly commercial buildings, and there are many people in the daytime, so they need high thermal comfort and high heating load. However, there are few people in commercial buildings at night, and the thermal comfort is low. Therefore, the heating load of the buildings at night is low.

Instantaneous heating load on the customer side is variable, so heating regulation is required during operation. In this paper, temperature regulation is utilized as a centralized regulation method for the hot water heating system, that is, the mass flow rate of heating water is unchanged, and only the temperature of the supply water is changed. Fig. 4(b) shows the variation in the temperature of the supply and return water in the heating system regarding the number of days. At the beginning of the heating period, the required heating load on the customer side is low, the temperature of the supply water is slightly lower, the temperature of the return water is high, and the temperature difference between the supply and return water is small; at this stage, the average temperature of the supply water is 45.29 ℃, the average temperature of the return water is 34.43 ℃, and the average temperature difference between supply and return water is 10.86 ℃. As time passes, the ambient temperature gradually decreases, the heating demand on the customer side becomes higher, the temperature of the supply water rises continuously up to 48.45 ℃, the temperature of the return water gradually decreases, down to 32.92 ℃, and the maximum temperature difference between supply and return water is up to 15.53 ℃. At the later stage of the heating period, the ambient temperature gradually rises, the heating load of the customers is lower, the temperature of the supply water gradually decreases, the temperature of the return water gradually increases, and the temperature difference between the supply and return water becomes smaller, at this stage the average temperature of the supply water is 45.63 ℃, the average temperature of the return water is 35.86 ℃, and the average temperature difference between supply and return water is 9.77 ℃.



(a) (b)

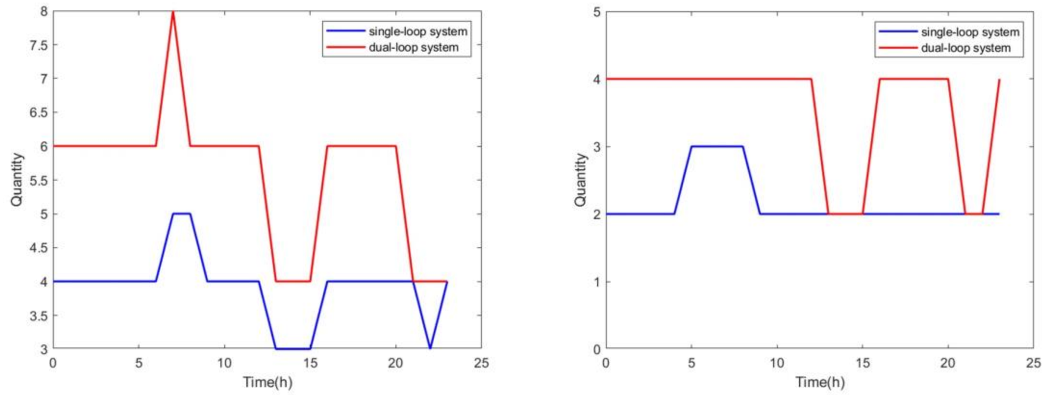
Fig. 4. (a) Hourly heating load of buildings in the heating period in this area; (b) Temperature of the supply and return water during the heating period.

2.4. Control strategy of heat pump

Based on the hourly heating load curve and the temperature variation curve of the supply and return water obtained from the above simulation throughout the heating period, this paper carries out the analysis of the year-round control strategy of the booster heat pump system, which controls the heat production by controlling the compressor on and off, and the higher the heating load, the more the number of compressors on. When the heating load is lower than the rated heat capacity of one unit, only one heat pump unit is turned on. It is important to note that two compressors need to be started for the dual-loop heat pumps for each unit.

On the day with the highest heating load during the whole heating period, the number of started compressors hour by hour for the North and South areas are shown in Fig. 5(a) and 5(b), respectively. It can be seen that the number of started compressors is higher in the North area than in the South area due to the difference in heating load. Since the dual-loop systems contain two compressors in one unit, the number of started compressors is greater than or equal to that of the single-loop systems. At night, there are few people in the commercial buildings, the heating load is low, and the number of started compressors is small; during the daytime, the number of people in the commercial buildings increases, the heating load rises, and the number of started compressors increases and reaches the highest from 7:00 a.m to 9:00 a.m. After 9:00 a.m, solar heat radiation gradually becomes more robust, the heating load decreases, and the number of started compressors decreases. From 11:00 a.m to 3:00 p.m, the heating load is lowest and the compressor is turned on the least.

During the heating period, solar radiation, ambient temperature, as well as the number of people in the building, vary almost cyclically, which means that the trend of the number of compressors starting and stopping each day is the same, and there will only be quantitative differences, so the day with the highest heating load is chosen for the control strategy analysis to be more representative.



(a) (b)

Fig. 5. (a) Number of compressors started by the hour in North area; (b) Number of compressors started by the hour in South area.

3. Calculation and result analysis of booster heat pump system

3.1. Thermal cycle calculation process of the heat pump unit

The temperature of the supply and return water and heating load obtained in section 2.3 are used as input to calculate the parameters of the thermal process for the conventional single-loop system and the new dual-loop system based on the control strategy of compressors, and the calculated parameters include the condensation and evaporation temperature temperatures, condensation and evaporation pressures, water-side mass flow rate, refrigerant mass flow rate, the heating capacity, heat taking and power consumption.

For the whole dual-loop system, the heating capacity, power consumption and COP of the system can be calculated by equations (1), (2) and (3). The heating capacity and power consumption of the whole system are the sum of the two loops. Equations (4) and (5) are the power consumption calculation process of the low-temperature loop, and the calculation process of the high-temperature loop is similar to that of the low-temperature loop.

$$Q_e = cm_1(t_{w,1,i} - t_{w,1,o}) \tag{1}$$

$$Q_c = cm_2(t_{w,2,o} - t_{w,2,i}) \tag{2}$$

$$COP = Q_c/W \tag{3}$$

$$m_{r1} = Q_{c1}/(h_2 - h_3) \tag{4}$$

$$W_1 = m_{r1}(h_2 - h_1) \tag{5}$$

Where, Q_c is the heating capacity of the whole system, kW; Q_e is the quantity of heat taken from the low-temperature heat source side, kW; c is the specific heat capacity of water, J/(kg·℃); m_1 is the mass flow rate of the heat source water, m³/h; m_2 is the mass flow rate of the supply water, m³/h; m_r is the mass flow rate of refrigerant, kg/s; W is the power consumption of the compressors, kW; COP is the coefficient of performance; $t_{w,1,i}$ is the inlet temperature of low-temperature heat source water, ℃; $t_{w,2,i}$ is the temperature of the return water, ℃; $t_{w,1,o}$ is the outlet temperature of low-temperature heat source water, ℃; $t_{w,2,o}$ is the temperature of the supply water, ℃.

3.2. Flowchart for calculating dual-loop booster heat pump

Since a dual-loop heat pump system has two loops and the two loops interact, the calculation process differs from that of a single-loop heat pump. Using the heat balance equation of the water side and the refrigerant side, input the known temperatures of the supply water and the return water, the inlet and outlet temperatures of the heat source water side, the average temperature of the inlet and outlet temperatures of the hot water side and the average temperature of the inlet and outlet temperatures of the heat source water side can be selected as the assumed temperature of the middle point respectively, and after repeated iterations to reach equilibrium, simulations are performed to calculate the low-temperature loop, high-temperature loop and the overall unit performance parameters. The flowchart of the calculation of the dual-loop heat pump is shown in Fig. 6 below.

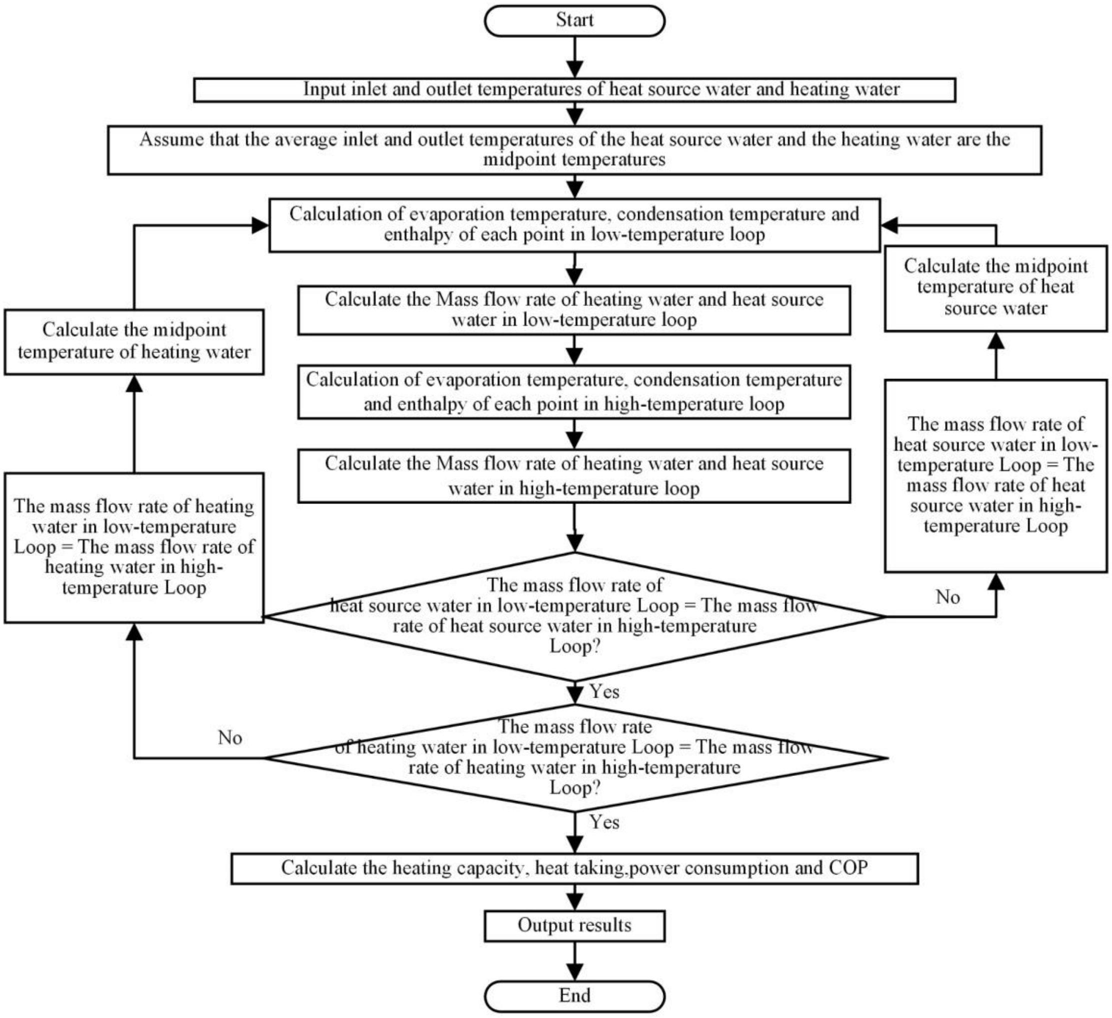


Fig. 6. Flowchart for calculating the dual-loop booster heat pump.

3.3. Verification of calculation results

In order to verify the accuracy of the calculation results in this paper, the working condition of supply/return water temperature of 60/50 ℃ and heat source water inlet/outlet temperature of 30/25 ℃ are calculated and compared with the results in Ref. [22]. The results are shown in Table 2. From Table 2, the deviation of COP is 4.36%, the deviation of power consumption is 4.82% and the deviation of heat capacity is 9.06% compared with the data in the literature, which are less than 10%, which can indicate the reliability and accuracy of the calculation results.

Table 2. Calculated results compared with experimental results in Ref. [22]

Items	Literature	This paper	Deviation (%)
COP	6.70	6.42	4.36
Power consumption (*kW*)	1418.0	1352.8	4.82
Heating capacity (*kW*)	9550.0	9492.5	9.06

3.4. Calculation results

Calculations are performed according to the calculation procedure shown in Fig. 7, keeping the inlet temperature of heat source water at 28 ℃ and outlet temperature at 18 ℃, heat transfer temperature difference of the heat exchanger at 3 ℃. The inlet and outlet temperatures of heating water vary according to the curves shown in Fig. 4(b).

Fig. 7 shows the dynamic variation of the COP of the conventional single-loop booster heat pump and the new dual-loop booster heat pump in terms of days. Under the same conditions, the COP of the dual-loop heat pump is significantly higher than that of the conventional single-loop heat pump. The COP of the single-loop heat pump and the dual-loop system has roughly the same trend over time, both decrease first and then increase, mainly because the temperatures of the supply and return water are different at different times, as shown in section 2.3, the temperature of the supply water increases first and then decreases over time during the heating period. When the temperature of the supply water increases, the system needs to reach a higher condensation temperature. The compressor's compression ratio increases, the refrigerant mass flow rate decreases, and the system performance decreases. The average COP of the single-loop heat pump was 5.42 and the average COP of the dual-loop system was 6.34, with a difference of 0.92. The highest COP of the single-loop heat pump was 6.28 and the lowest was 5.03, with a variation of 1.25, and the highest COP of the dual-loop heat pump was 7.12 and the lowest was 6.01, with a variation of 1.11.

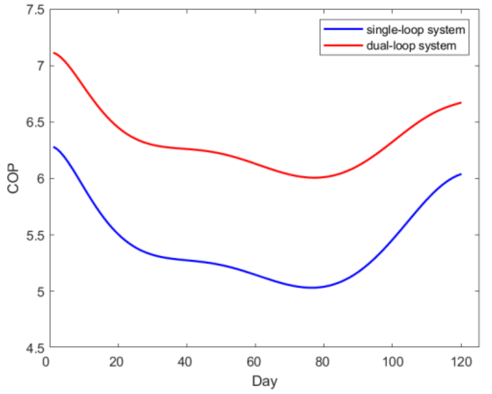


Fig. 7. COP of booster heat pump systems.

3.5. Energy saving effect

Fig. 8 shows the daily power consumption of the traditional single-loop booster heat pump and the dual-loop booster heat pump in the North area. The horizontal coordinate is time and the vertical coordinate is the power consumption of the heat pump. The red curve represents the dual-loop heat pumps and the blue curve represents the single-loop heat pumps. It can be seen that in the middle of the heating period, the power consumption is higher than that at the beginning and end of the heating period, which is the same as the trend of the heating load. The power consumption of the dual-loop heat pumps is generally lower than that of the single-loop heat pumps, which is more obvious when the heating load is high.

After calculation, this ultra-low temperature district heating system can produce 4260 GJ of heat per year during the heating period, of which the single-loop heat pumps need to consume 0.217 million kW·h of electric energy and the dual-loop heat pumps need to consume 0.183 million kW·h of electric energy. In the whole heating period, compared with the single-loop heat pump system, the dual-loop heat pump system saves 0.034 million kW·h of electric energy, and the electricity saving rate is up to 15.6%.

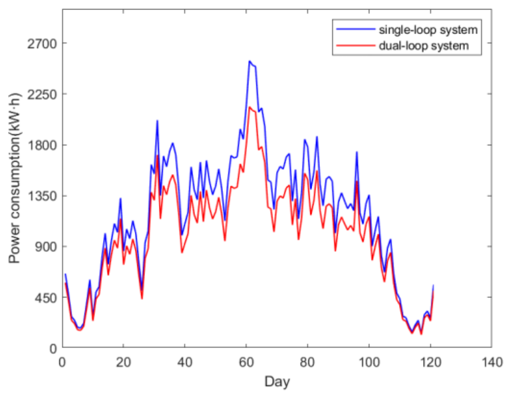


Fig. 8. Power consumption of the booster heat pump.

4. Conclusions

In this paper, a new dual-loop booster heat pump for ultra-low temperature district heating is designed and applied to a gas boiler flue gas deep recovery project in Beijing. Simulations were performed using DeST software to obtain the hourly heating load for the entire heating period, and then the annual energy consumption and COP of the dual-loop booster heat pump system were calculated and analyzed, with the following conclusions:

The heating load of the building is affected by the ambient temperature more obviously, from the beginning to the end of the heating period, the heating load of the buildings rises first and then decreases, in the middle of the heating period when the weather is cold, the heating load is larger, at the beginning and the end of the heating period the heating load of the buildings is smaller, among which the maximum heating load of the buildings in the North area can reach up to 710.75 kW, and the highest heating load of the buildings in the South area is 395.74 kW. The waste heat recovery capacity of the booster heat pump designed in this paper can fully meet the heating demand of this part of the building.

Compared with the traditional single-loop heat pump, the dual-loop heat pump has a significant energy-saving effect, with an average COP increase of 0.92. The traditional single-loop heat pumps need to consume 0.217 million kW·h of electric energy in the whole heating period. In comparison, the dual-loop heat pumps consume 0.183 million kW·h, saving 0.034 million kW·h of electric energy, with an electricity saving rate of up to 15.6%.

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