HIGH TEMPERATURE CASCADE HEAT PUMP SYSTEM WITH DOUBLE MEDIUM AND LOW TEMPERATURE HEAT SOURCES

by

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In response to the call for carbon neutrality and control of CO_2 emission, this paper proposes a high temperature cascade heat pump system with double medium and low temperature heat sources. Compared with those with a single heat source, the new system has obvious advantages in energy saving and carbon emission. An experiment is designed where the temperature of medium temperature heat source keeps unchanged, revealing that, compared with a single low temperature heat source, the heating capacity of low temperature heat source reduces by 2.9%, the heating capacity of medium temperature heat source increases by 31.1%, the total power consumption of the heat pump increases by 3%, and the heating capacity of the heat pump increases by 4.3%.

Key words: *high temperature heat pump, cascade, low temperature heat source, medium temperature heat source*

Introduction

Along with the improvement of living standards, people have higher and higher requirements for environmental comfort [1], so the energy consumption of heating, air conditioning and hot water in buildings is also increasing. In China, heating, air conditioning and hot water supply account for 80% of building energy consumption. According to 2019 China Building Energy Consumption Research Report published in a *Chinese Journal of Construction and Architecture*, *7* (2020), 4. pp. 30-39, China's building energy consumption accounted for 21.10% of the total national energy consumption in 2017.

China's large energy demand, single energy structure and low energy utilization rate have seen a high carbon emission. At the same time, in response to the call for carbon neutrality and peak CO_2 emission [2], China has already committed to peak CO_2 emissions before 2030 and to achieve carbon neutrality before 2060. China called for accelerated efforts for a better industry and energy structure, which enables to reduce the peaking of coal consumption at an early date while bolstering the development of new energy.

Heat pump [3] is an energy transfer and utilization system that consumes part of high mass energy or high temperature potential energy to transfer heat energy from low temperature object to high temperature object through thermal cycle. From the perspective of sci-

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entific energy use, heat pump is the only technical method that can realize *energy level improvement* and realize the rational utilization of both high and low grade energy. Therefore, vigorously developing heat pump technology can effectively increase energy utilization and reduce carbon emissions.

Extensive technical research on the cascade heat pump were conducted, and much achievement was obtained [4, 5]. The performance of medium and high temperature heat pump mixture was analyzed in details from different angles [6-9].

This paper proposes a high temperature cascade heat pump system with medium-low temperature dual heat sources, this is a special form of cascade heat pump systems. It can not only recycle single medium temperature waste heat, but also compound medium and low temperature heat sources, so it can achieve the purpose of preparing high temperature hot water.

Theoretical analysis

Figure 1 is a schematic diagram of the new designed high temperature cascade heat pump system with medium-low temperature dual heat sources. Compared with the traditional two-stage steam compression cascade refrigeration cycle, the present one consists of two single-stage thermodynamic cycles: low temperature stage and high temperature stage. Firstly, the cycle conditions and use purposes are different. The R410A and R124 are used, respectively, as low temperature and high temperature heat pump cycle working fluids. The operation temperature of the cascade cycle is high, and the purpose is to produce 80 °C high temperature hot water. Secondly, the composition of the system is different. The system includes a three medium heat source condensing evaporator. Through the low temperature evaporator and heat source condensing evaporator, the single medium temperature waste heat can be recycled, and double medium and low temperature heat sources can be combined. The circulation process is the low temperature working medium evaporates in the evaporator, absorbs the heat from the low temperature heat source, and becomes low temperature and low pressure steam. After being compressed by the low temperature compressor, the high temperature and high pressure gas enters the heat source condensation evaporator, where it releases heat to the high temperature working medium, condenses into liquid state under a constant pressure, and becomes low-pressure wet steam after passing through the low temperature throttling device,

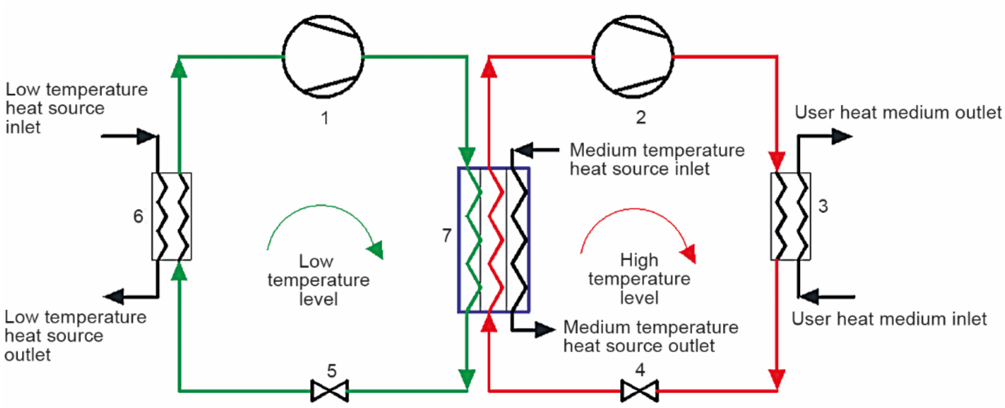

Figure 1. Schematic diagram of high temperature cascade heat pump system with medium-low temperature dual heat sources; *1 – low temperature compressor, 2 – high temperature compressor, 3 – high temperature condenser, 4 – high temperature stage throttling device, 5 – low temperature stage throttling device, 6 – low temperature evaporator, and 7 – heat source condensing evaporator*

then re-enters the evaporator to realize evaporation and heat absorption, and finally enters the low temperature compressor to complete the low temperature cycle. The high temperature working medium evaporates in the heat source condensing evaporator, absorbs the heat from the low temperature working medium, and becomes low temperature and low-pressure steam. After being compressed by the high temperature compressor, it enters the condenser as high temperature and high pressure gas, releases heat to the heat medium on the user side, condenses into liquid state under a constant pressure, and becomes low pressure wet steam after passing through the high temperature throttling device, then re-enters the heat source type condensing evaporator to realize evaporation and heat absorption, and finally enters the high temperature stage compressor to complete the high temperature stage cycle.

In order to facilitate theoretical analysis and calculation, we make the following assumptions for the thermal cycle of high temperature cascade heat pump system with medium-low temperature dual heat sources. The compression process is isentropic, and there is no irreversible loss in the compression process. The evaporation and condensation processes of working medium are isobaric processes without pressure loss. The throttling process is an isenthalpic process without throttling loss. The working medium has no state change in the connecting pipeline between equipment. The liquid hammer of the compressor and ensure that the working medium has a certain degree of superheat when leaving the evaporator and the working medium has a certain degree of undercooling when it comes out of the condenser. Figures 2 and 3 are the log*p*-*h* diagram and the *T*-*S* diagram, respectively, of thermal cycle of the heat pump system based on the above assumptions.

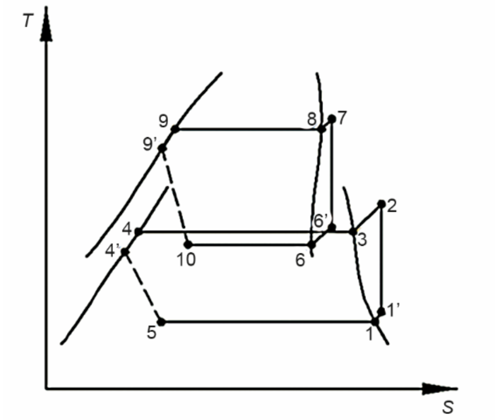

Figure 2. The Log*p*-*h* diagram

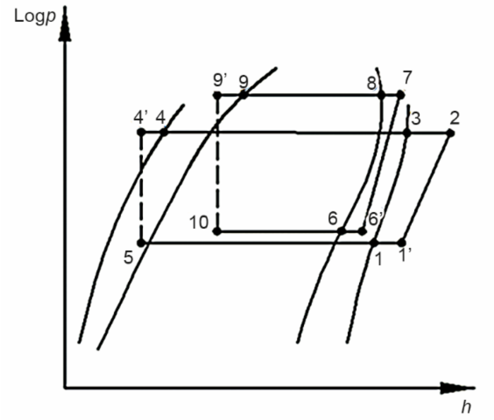

Figure 3. The *T*-*S* diagram

The theoretical cycle thermodynamic calculation under the above assumptions is as follows [10]:

High temperature stage heat pump cycle

– Heat absorption per unit mass: $q_{\mathrm{H}\varepsilon}$[kJkg^{-1}]

$$q_{\mathrm{H}\varepsilon} = h_{6'} - h_{10} \tag{1}$$

– Power consumption per unit mass: w_{H}[kJkg^{-1}]

$$w_{\mathrm{H}} = h_7 - h_{6'} \tag{2}$$

– Heating capacity per unit mass: $q_{\mathrm{Hc}}[\mathrm{kJkg}^{-1}]$

$$q_{\mathrm{Hc}} = h_{9'} - h_7 \tag{3}$$

– Working medium mass-flow: $m_{\mathrm{H}}[\mathrm{kgs}^{-1}]$

$$m_{\mathrm{H}} = \frac{Q_{\mathrm{Hc}}}{q_{\mathrm{Hc}}} \tag{4}$$

– Heat absorption of heat pump: $Q_{\mathrm{H}e}[\mathrm{kW}]$

$$Q_{\mathrm{H}e} = m_{\mathrm{H}} q_{\mathrm{H}e} \tag{5}$$

– Heat pump power consumption: $W_{\mathrm{H}}[\mathrm{kW}]$

$$W_{\mathrm{H}} = m_{\mathrm{H}} w_{\mathrm{H}} \tag{6}$$

Low temperature heat pump cycle

– Heat absorption per unit mass: $q_{L\varepsilon}[\mathrm{kJkg}^{-1}]$

$$q_{L\varepsilon} = h_{1'} - h_5 \tag{7}$$

– Power consumption per unit mass: $w_L[\mathrm{kJkg}^{-1}]$

$$w_L = h_2 - h_{1'} \tag{8}$$

– Heating capacity per unit mass: $q_{L\mathrm{c}}[\mathrm{kJkg}^{-1}]$

$$q_{L\mathrm{c}} = h_{4'} - h_2 \tag{9}$$

– Working medium mass-flow: $m_L[\mathrm{kgs}^{-1}]$

$$m_L = \frac{Q_{L\mathrm{c}}}{q_{L\mathrm{c}}} \tag{10}$$

– Heat absorption of heat pump: $Q_{Le}[\mathrm{kW}]$

$$Q_{Le} = m_L q_{Le} \tag{11}$$

– Heat pump power consumption: $W_L[\mathrm{kW}]$

$$W_L = m_L w_L \tag{12}$$

Experimental data analysis

Experimental scheme

– *Single low temperature heat source mode*

Under the single low temperature heat source mode, the variation law of the performance of the cascade heat pump system is mainly investigated. The specific experimental conditions are shown in tab. 1. In order to keep the inlet temperature of the low temperature heat source at 15 °C under the design working condition, the flow rate is adjusted.

– *Medium and low temperature dual heat source mode*

Under the dual medium and low temperature heat source mode, the variation law of the performance of the cascade heat pump system is mainly investigated with the change of medium temperature heat source flow, inlet temperature and low temperature compressor frequency, when the low temperature heat source remains unchanged. See tab. 2 for specific experimental conditions. In order to keep the inlet temperature of medium temperature heat source at 48 ℃ under the design working condition, the flow rate is adjusted.

Table 1. Single low temperature heat source model

Low temperature heat source		User heat medium		Compressor frequency	
Inlet temperature [℃]	Flow [m^3h^{-1}]	Inlet temperature [℃]	Flow [m^3h^{-1}]	Low temperature level [Hz]	High temperature level [Hz]
15	0.35	72	1.05	38	54
	0.53				
	0.70				
	0.88				
	1.10				

Table 2. Medium and low temperature dual heat source mode

Medium temperature heat source		Low temperature heat source		User heat medium		Compressor frequency	
Inlet temperature [℃]	Flow [m^3h^{-1}]	Inlet temperature [℃]	Flow [m^3h^{-1}]	Inlet temperature [℃]	Flow [m^3h^{-1}]	Low temperature level [Hz]	High temperature level [Hz]
48	0.40	15	0.70	72	1.05	38	54
	0.60						
	0.80						
	1.00						
	1.17						

Data analysis

– *Cascade intermediate temperature and cascade heat transfer temperature difference*

Figure 4 shows the variation curves of cascade intermediate temperature, T_m, high temperature, $T_{\mathrm{H},e}$, evaporation temperature and low temperature, $T_{L,\mathrm{c}}$, condensation temperature with medium temperature heat source flow under medium and low temperature dual heat source mode. The data in the figure shows that as the flow rate of medium temperature heat source increases from 0.40-1.17 m^3/h, the evaporation temperature of high temperature stage increases from 42.4-45 ℃. The temperature in the middle of stacking rises from 45.4-48 ℃. The condensation temperature of low temperature stage rises from 48.5-51 ℃. Figure 5 shows the variation curve of cascade heat exchange temperature difference ΔT with medium temperature heat source flow. The data in the figure shows that the temperature difference of cascade heat exchange changes within the range of 6~6.5 ℃, and the amplitude is relatively small.

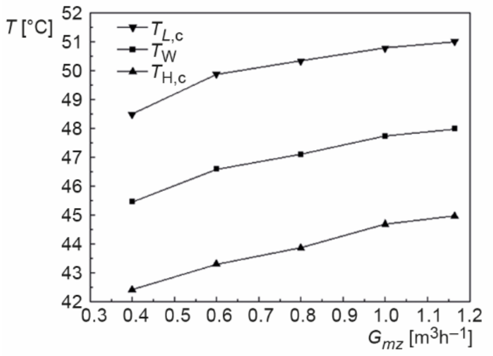

Figure 4. Variation of cascade intermediate temperature, high temperature stage evaporation temperature and low temperature stage condensation temperature with medium temperature heat source flow

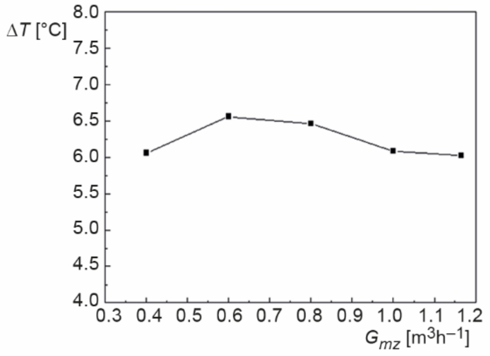

Figure 5. Variation of cascade heat exchange temperature difference with medium temperature heat source flow

– *Heating capacity of low temperature heat source*

Figure 6 shows the variation curve of low temperature heat source heating capacity of cascade high temperature heat pump system with medium temperature heat source flow under medium and low temperature dual heat source mode. The data in the figure shows that as the flow of medium temperature heat source increases from 0.40-1.17 m³/h, the heating capacity of low temperature heat source decreases slightly, from 5.55-5.39 kW, a decrease of 2.9%. The reason for the change is: the increase of medium temperature heat source flow increases the condensation temperature of low temperature stage, while the increase of evaporation temperature is relatively small, so that the heat supply of low temperature heat source decreases slightly under the comprehensive effect of reducing the heat absorption per unit mass and slightly increasing the quality of working medium.

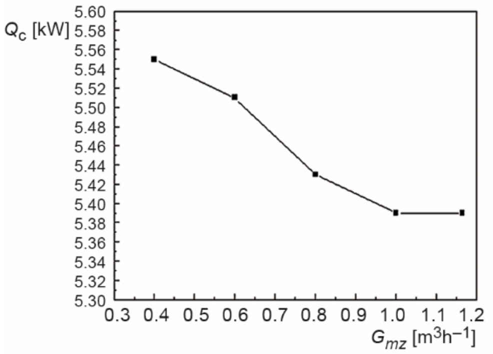

Figure 6. Variation of heating capacity of low temperature heat source with medium temperature heat source flow

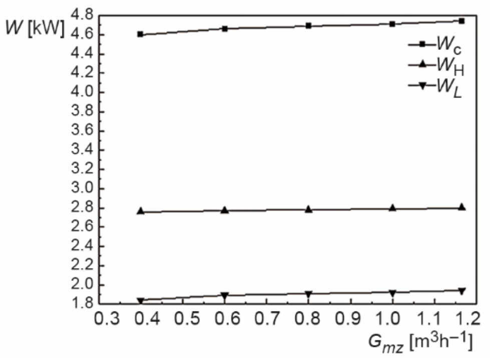

Figure 7. Variation of power consumption with medium temperature heat source flow

– *Power waste*

Figure 7 shows the variation curves of high temperature heat pump power consumption, low temperature heat pump power consumption and total power consumption of cascade heat pump with medium temperature heat source flow under medium and low temperature dual heat source mode. The data in the figure shows that the power consumption of high temperature heat pump does not change significantly as the flow of medium temperature heat source increases from 0.40-1.17 m³/h. The power consumption of low temperature heat pump increased slightly, from 1.84-1.94 kW, an increase of 0.1 kW, an increase of 5.4%. The total power consumption of cascade heat pump increased slightly, from 4.6-4.74 kW, an increase of 0.14 kW, an increase of 3%.

– *Heating capacity of cascade heat pump*

Figure 8 shows the variation curve of heating capacity of cascade heat pump system with medium temperature heat source flow under medium and low temperature dual heat source mode. The data in the figure shows that as the flow of medium temperature heat source increases from 0.40-1.17 m³/h, the heating capacity of cascade heat pump and hot water supply temperature increase, and the heating capacity of cascade heat pump increases from 11.39-11.88 kW, an increase of 0.49 kW, an increase of 4.3%

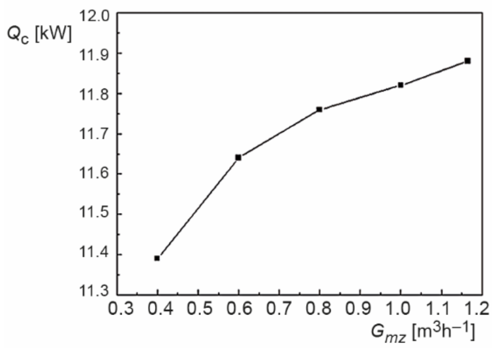

Figure 8. Variation of heating capacity of cascade heat pump with medium temperature heat source flow

Discussion and conclusions

The future research frontier on the high temperature cascade heat pump system includes mainly the following three issues: the aeroelastic model [11], the control technique [12-19], and the optimization method [20-22].

This paper proposes the high temperature cascade heat pump system with medium-low temperature dual heat sources, and elucidates its working principle and characteristics theoretically and experimentally. The experimental results are as follows.

- The heat pump system can not only absorb heat from a single low temperature heat source, but also make compound use of the double medium and low temperature heat sources, effectively recover the medium temperature waste heat, and realize the purpose of preparing 80 °C high temperature hot water. In addition, the high temperature heat pump cycle can be operated separately to recycle a single medium temperature waste heat to produce high temperature hot water.
- Under the working mode of medium and low temperature heat sources, on the premise of maintaining the inlet temperature and flow of low temperature heat source at 15 °C and 0.70 m³/h respectively, the flow of medium temperature heat source has a certain impact on the performance of cascade heat pump system. Specifically, when the inlet temperature of the medium temperature heat source is 48 °C and the flow of the medium temperature heat source increases from 0.40-1.17 m³/h. The overlapping load ratio of medium temperature heat source increases from 0.15-0.19. The total power consumption of cascade heat pump increased from 4.6-4.74 kW, an increase of 0.14 kW, an in-

crease of 3%. The heating capacity of cascade heat pump increased from 11.39-11.88 kW, an increase of 0.49 kW, an increase of 4.3%.

- According to the performance change law of the cascade heat pump system under the above medium and low temperature dual heat source working mode, changing the refrigerant flow can improve the heating efficiency of the heat pump and reduce energy consumption, but the improvement effect is not significant.

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