EXPERIMENTAL STUDY ON HIGH TEMPERATURE HEAT PUMP SYSTEM WITH A DOUBLE HEAT SOURCE CASCADE

by

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Original scientific paper
https://doi.org/10.2298/TSCI2303845B

In order to improve the thermal performance of a high temperature heat pump system, to realize the efficient heat recovery of industrial waste heat, and to make the combined utilization of low and medium temperature heat sources, a high temperature heat pump system with a double heat source cascade is proposed, which can absorb heat from industrial waste heat and the system is capable of heating water up to the required high temperature. The performance of the system is tested and analyzed. It is found that the inlet temperature of the medium temperature heat source has a significant impact on the performance of the heat pump system under working mode of the medium and low temperature heat sources. When the inlet temperature of the intermediate temperature heat source rises from 42 ℃ to 53 ℃, the heating capacity of the cascade heat pump increases by 18.6%, and its performance coefficient increases by 8.9%. This paper provides a reference for the high efficiency of the cascade high temperature heat pump technology.

Key words: *high temperature heat pump, dual heat sources, system performance, cascade type*

Introduction

The energy used in traditional boiler heating is only used once, and there is no secondary or third effective utilization, which greatly reduces the energy utilization efficiency. Heat pump obtains several times its heat by consuming relatively less high-grade energy, which means it is an efficient and energy-saving technology. Moreover, it is widely used in construction, industry and other fields. It meets the very requirement of a green and low-carbon development. At present, the normal temperature heat pump (heating temperature below 50 ℃) is basically mature and has been commercialized, which plays a positive role in global carbon emission reduction.

On the one hand, the low-carbon technology is the key to the development of low-carbon economy, on the other hand it is important to alleviate climate warming, to overcome energy crisis and to have sustainable development [1]. In the technical process, much attention was paid on improving energy efficiency and using industrial waste heat to provide hot water for housing, a feasible method is to use a high temperature heat pump [2]. The heat

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pump heating technology is an efficient and energy-saving technology, which is widely used in construction, industry and other fields. At present, the technology of high temperature heat pump for producing high temperature hot water is not mature [3]. The high temperature heat pump technology can use a single low temperature working medium for efficient heat recovery of industrial low temperature waste, so that low and medium temperature heat sources can be effectively utilized. It overcomes the disadvantages of traditional heat pumps in high compressor compression ratio, and excessive exhaust temperature. At the same time, the new heat pump recycles a large number of industrial waste heat resources and reduces the thermal pollution caused by industrial waste heat emission [4-6]. Almost all machines produce industrial waste heat [7-10], and it becomes a hot topic to optimally use the waste heat [11]. As for the high temperature heat pump system, authors in [12-14] studied the high temperature heat pump with industrial waste heat recovery as the main heat source. Authors in [15-17] applied the air replenishment technology to the high temperature heat pump, although the heating capacity increased, the power consumption of the compressor also increased significantly. Because the high temperature heat pump system has high condensation temperature, thus it is not suitable to use industrial waste heat with relatively high temperature as evaporator heat source for working medium with low critical temperature. It has broadly development prospects to efficiently recover industrial waste heat, and to make use of relatively low temperature heat sources such as air in the environment, and to select the best working condition.

To solve these problems, this paper proposes a high temperature heat pump system with a medium and low temperature double heat source cascade. The first stage of the system takes R410A as the working medium, which absorbs heat from relatively low temperature heat sources such as air, and in the second stage, the working medium R124 with higher critical temperature is used to evaporate and to absorb heat from the high temperature working medium R410A and waste heat condensed by the heat source condensation evaporator, and the water is heated to the required high temperature in the condenser. Through the low temperature evaporator and heat source condensation evaporator, the medium temperature waste heat can be effectively recovered to achieve the purpose of preparing high temperature hot water. The performance of heat pump system is determined by many factors. By studying the influence of its key factor – the effect of the inlet temperature of medium temperature heat source on the system efficiency, researchers select an appropriate temperature range to ensure the optimal performance of the system. The theoretical model of the above system is established and its performance is analyzed.

Theoretical process analysis of the high temperature heat pump system with a medium and low temperature double heat source cascade

Figure 1 is the flow chart of the proposed high temperature heat pump system with a medium and low temperature double heat source cascade. The R410A working medium with low critical temperature reaches the saturated vapor state after absorbing the heat of low temperature heat sources such as air in the evaporator – 6, and then enters the compressor – 1 for compression, as a result, high temperature and high-pressure gas is obtained. In the heat source condensing evaporator – 7, it releases heat to the second stage circulating working medium, condenses at constant pressure to liquid state, and becomes low temperature and low-pressure wet vapor after passing through the first stage throttling device – 5, reenters evaporator – 6 to complete the first stage cycle. At the same time, the working medium R124 with higher critical temperature in the second stage evaporates and absorbs the heat from the first stage circulation and medium temperature heat source in the heat source condensing evaporator – 7 and becomes low temperature and low pressure steam. After being compressed by the second stage compressor – 2, it enters the condenser – 3 as high temperature and high pressure gas, where it releases heat to the heat medium on the user's side and condenses into a liquid state under constant pressure. After passing through the second stage throttling device, it becomes low pressure wet steam and re-enters the heat source condensation evaporator – 7 to complete the second stage cycle.

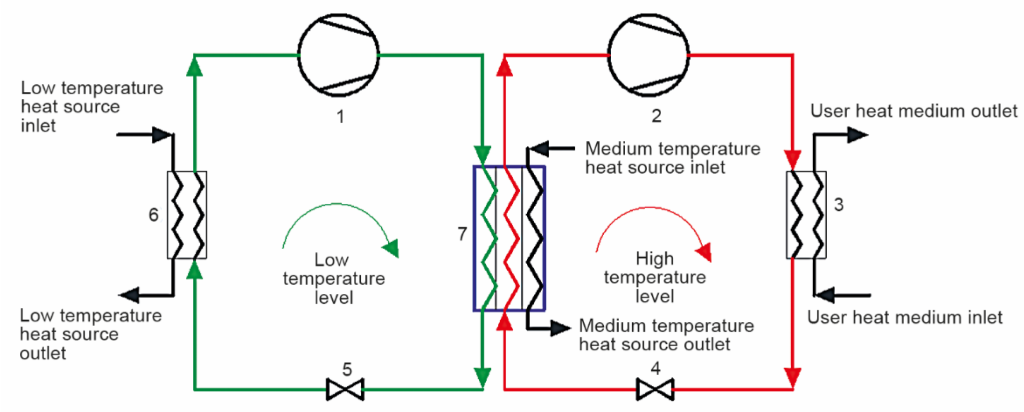

Figure 1. Flow chart diagram of medium and low temperature double heat source cascade high temperature heat pump system; *1 – low temperature compressor, 2 – high temperature compressor, 3 – high temperature condenser, 4 – high temperature throttling device, 5 – low temperature throttling device, 6 – low temperature evaporator, and 7 – heat source condensing evaporator*

In order to facilitate theoretical analysis and calculation, the following assumptions are made for the system.

- The compression process is isentropic, that is, there is no irreversible loss in the compression process.
- The pressure loss of working medium flowing in evaporator and condenser is ignored, and the heat transfer process in each heat exchanger is set as constant pressure process, that is, there is no pressure loss.
- The throttling process is an isenthalpic process, that is, there is no throttling loss.
- The working medium does not change state in the connecting pipeline between equipment. Based on the above assumptions, the calculation model is established according to the conservation laws of mass and energy.

The theoretical cycle thermodynamic calculation under the previous assumptions is presented at fig. 2.

According to the First law of thermodynamics, the following energy balance equation can be obtained. The condensation heat release of the low temperature stage, Q_{Lc}, is equal to the sum of the heating capacity of the low temperature heat source, Q_{Le} and the power consumption of the low temperature heat pump, W_{L}:

$$Q_{\mathrm{Le}} + W_{\mathrm{L}} = Q_{\mathrm{Lc}} \tag{1}$$

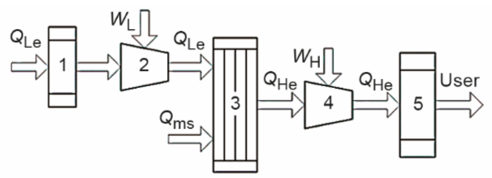

Figure 2. Schematic diagram of energy transfer and transformation

The condensation heat release of the high temperature stage, Q_{Hc}, is equal to the sum of the heat supply of the high temperature stage, Q_{He}, and the power consumption of the high temperature stage heat pump, W_H:

$$Q_{He} + W_H = Q_{Hc} \tag{2}$$

The heat supply of high temperature level, Q_{He}, is equal to the sum of the heat supply of low temperature heat source, Q_{Lc}, and medium temperature heat source, Q_{ms}:

$$Q_{Lc} + Q_{ms} = Q_{He} \tag{3}$$

The overlapping load ratio of medium temperature heat source, α_{ms}, is equal to the ratio of heat supply of medium temperature heat source, Q_{ms}, to heat absorption of high temperature stage, Q_{He}:

$$\alpha_{ms} = \frac{Q_{ms}}{Q_{He}} \tag{4}$$

The COP of the cascade heat pump is:

$$COP_c = \frac{Q_{Hc}}{W_L + W_H} = \frac{COP_L COP_H}{COP_L + (1-\alpha_{ms})COP_H - (1-\alpha_{ms})} \tag{5}$$

where COP_c is the performance coefficient of cascade heat pump, COP_L – the performance coefficient of low temperature heat pump, and COP_H – the performance coefficient of high temperature heat pump.

Experimental study on performance of medium and low temperature dual heat source working mode

During the cascade operation, the medium and low temperature double heat source operation mode is adopted, that is, during the cascade operation, the system absorbs heat from the low temperature heat source and the medium temperature heat source at the same time. The experimental design conditions are shown in tab. 1.

In the medium and low temperature dual heat source mode, the variation law of the performance of the cascade heat pump system with the change of the inlet temperature of the medium temperature heat source is mainly investigated when the low temperature heat source keeps the design working condition unchanged. The specific experimental conditions are shown in tab. 2.

The experimental process is: keep the flow of medium temperature heat source at 0.8 m^3/h, and adjust the inlet temperature to 42 ℃, 45 ℃, 48 ℃, 51 ℃, and 53 ℃, respectively. During the experiment, the inlet temperature and flow rate of the user heat medium are maintained as design conditions.

Table 1. Experimental design conditions

Parameter	Unit	Numerical value
Condensation temperature of high temperature stage	t_{Hc} [°C]	85
High temperature stage evaporation temperature	t_{He} [°C]	40
Low temperature condensation temperature	t_{Lc} [°C]	45
Low temperature evaporation temperature	t_{Le} [°C]	5
Cascade heat exchange temperature difference	ΔT [°C]	5
High and low temperature undercooling	[°C]	5
High and low temperature superheat	[°C]	5
User heat load	[kW]	10
High and low temperature compressor efficiency	–	0.65
Hot water supply at user side	[°C]	80
Hot water return	[°C]	72
Low temperature heat source into evaporator	[°C]	15
Low temperature heat source out of evaporator	[°C]	8

Table 2. Experimental conditions and methods of low temperature dual heat source mode

Medium temperature heat source		Low temperature heat source		User heat medium		Compressor frequency	
Inlet temperature [°C]	Flow [m^3h^{-1}]	Inlet temperature [°C]	Flow [m^3h^{-1}]	Inlet temperature [°C]	Flow [m^3h^{-1}]	Low temperature level [Hz]	High temperature level [Hz]
42	0.8	15	0.7	72	1.05	38	54
45							
48							
51							
53							

Analysis of experimental results

Figure 3 shows the variation curves of the cascade intermediate temperature, T_m, high temperature evaporation temperature, T_{He}, and low temperature condensation temperature, $T_{L,c}$, of the cascade high temperature heat pump system under the medium and low temperature dual heat source mode with the inlet temperature of the medium temperature heat source. The data in the figure show that as the inlet temperature of the medium temperature heat source increases from 42-53 °C. The evaporation temperature of the high temperature stage increases from 40.4-48.4 °C. The condensation temperature of low temperature stage rises from 46.3-54.3 °C. The temperature in the middle of stacking increased from 43.4-51.3 °C. The reasons for these changes are: the increase of the inlet temperature of the medium temperature heat source not only strengthens the effect of high temperature evaporation heat transfer, but also weakens the effect of low temperature condensation heat transfer, resulting in the obvious increase of high temperature evaporation temperature and low temperature condensation temperature.

Figure 4 shows the variation curve of low temperature heat source heating capacity, Q_{Ls}, of cascade high temperature heat pump system with medium temperature heat source inlet temperature under medium and low temperature dual heat source mode. The data in the figure shows that as the inlet temperature of medium temperature heat source increases from 42-53 °C, the heating capacity of low temperature heat source decreases from 5.64-5.31 kW, a decrease of 5.9%. The reason for the change is that the increase of the temperature of the medium temperature heat source reduces the heat absorption per unit mass of the low temperature stage cycle, and the working medium quality increases slightly, which reduces the heat supply of the low temperature heat source.

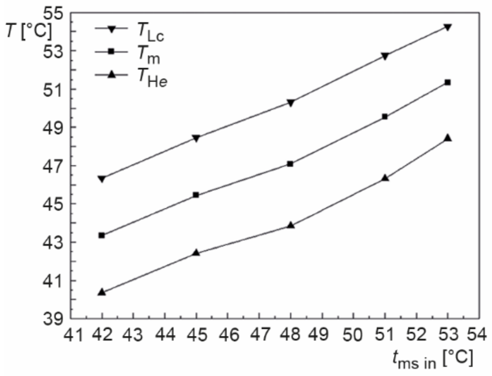

Figure 3. Variation of T_m, T_{He} and T_{Lc} with inlet temperature of medium temperature heat source

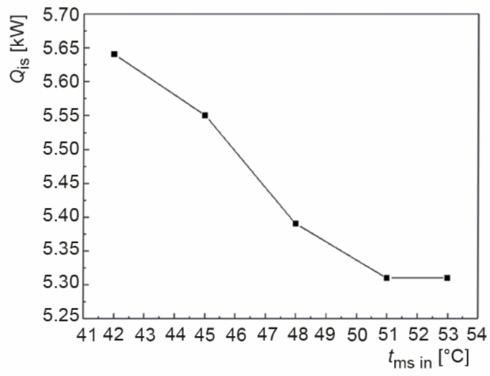

Figure 4. Variation of Q_{Ls} temperature heat source with inlet temperature of medium temperature heat source

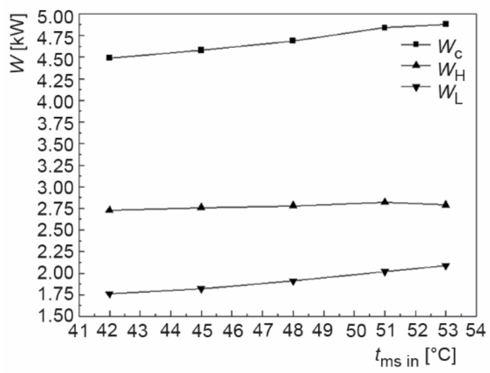

Figure 5. Variation of power consumption with inlet temperature of medium temperature heat source

Figure 5 shows the variation curves of high temperature heat pump power consumption, W_H, low temperature heat pump power consumption, W_L, and total power consumption, W_c, of cascade heat pump with the inlet temperature of medium temperature heat source under the medium and low temperature dual heat source mode. The data in the figure shows that as the inlet temperature of medium temperature heat source rises from 42-53 °C, the power consumption of high temperature heat pump does not change significantly. The power consumption of low temperature heat pump increased to a certain extent, from 1.76-2.09 kW, an increase of 0.33 kW, an increase of 18.8%. The total power consumption of cascade heat pump increased to a certain extent, from 4.49-4.88 kW, an increase of 0.39 kW, an increase of 8.7%. The reasons for the above changes are: the increase of the temperature of the medium temperature heat source reduces the specific work of the high temperature stage compression, increases the mass-flow of the working medium, and the change of the power consumption is small. For the low temperature stage cycle, the compression specific work increases, the change of refrigerant mass-flow is small, and its power consumption increases. The total power consumption of cascade heat pump shows an increasing trend under the influence of these two factors.

Figures 6 and 7, respectively, show the variation curves of the heating capacity, Q_c, of the cascade heat pump and the hot water supply temperature, $t_{hw,out}$, with the inlet temperature of the medium temperature heat source under the medium and low temperature dual heat source mode. The data in the figure shows that as the inlet temperature of medium temperature heat source rises from 42-53 ℃, the heating capacity of cascade heat pump and hot water supply temperature rise significantly, and the heating capacity of cascade heat pump rises from 10.54-12.5 kW, an increase of 1.96 kW, an increase of 18.6%. The temperature of hot water supply rises from 80.5-82.1 ℃. The reasons for the above changes are: the increase of the inlet temperature of the medium temperature heat source strengthens the evaporation heat transfer effect of the high temperature stage, the mass-flow of the working medium increases, the total heat transfer increases significantly, while the power consumption of the high temperature stage does not change significantly, so that the heating capacity of the cascade heat pump and the temperature of hot water supply increase significantly.

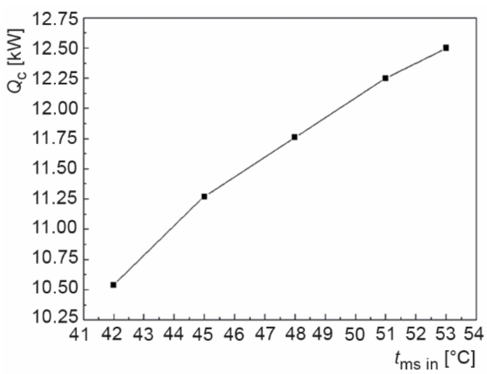

Figure 6. Variation of heating capacity of cascade heat pump with inlet temperature of medium temperature heat source

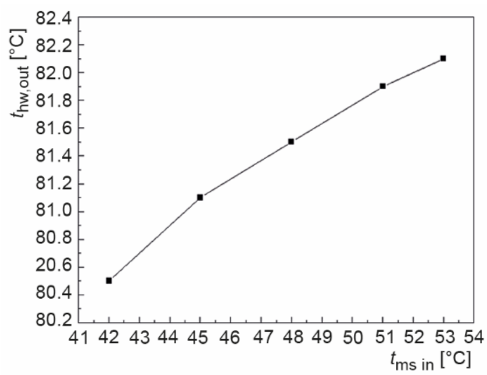

Figure 7. Variation of hot water supply temperature with inlet temperature of medium temperature heat source

Figure 8 shows the variation curves of low temperature heat pump performance coefficient, COP_L, high temperature heat pump performance coefficient, COP_H, and cascade heat pump performance coefficient, COP_c, with the inlet temperature of medium temperature heat source under the medium and low temperature dual heat source mode. The data in the figure shows that as the inlet temperature of medium temperature heat source rises from 42-53 ℃, under the trend of obvious increase in heating capacity of cascade heat pump and no obvious change in power consumption of high temperature heat pump, COP_H increases significantly, from 3.86-4.48, an increase of 16.1%. Under the trend that the heating capacity of low temperature heat source decreases and the power consumption of low temperature heat pump increases significantly, the COP_L decreases significantly, from 4.2-3.54, with a decrease of 15.7%. Under the combined influence of medium temperature heat source and high and low temperature cycle, the COP_c of cascade heat pump increased to a certain extent, from 2.35-2.56, an increase of 8.9%.

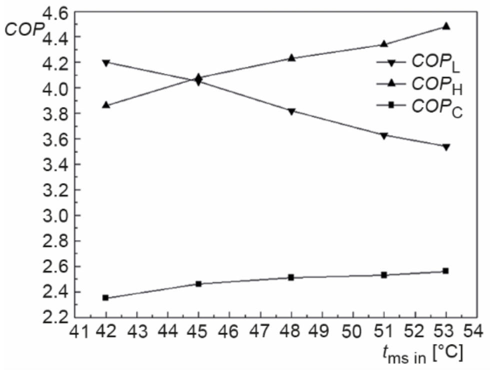

Figure 8. Variation of COP_L, COP_H, and COP_c with inlet temperature of medium temperature heat source

Conclusion

This paper can make conclusions as follows.

- The research shows that the dual heat source cascade high temperature heat pump system can better realize the organic integration of waste heat recovery high temperature heat pump and cascade high temperature heat pump technology and the synchronous compound utilization of medium and low temperature heat sources.
- Under the working mode of medium and low temperature dual heat sources, the inlet temperature of medium temperature heat source has a significant impact on the performance of cascade heat pump system. Specifically, when the flow rate of medium temperature heat source is 0.8 m^3/h and the inlet temperature of medium temperature heat source rises from 42-53 ℃, the total power consumption of cascade heat pump increases by 8.7%. The heating capacity of cascade heat pump increased by 18.6%. The performance coefficient COP_c of cascade heat pump increased by 8.9%.
- The double heat source cascade high temperature heat pump can maintain high performance by adjusting the temperature of medium temperature heat source, which plays a positive role in accelerating the application of high temperature heat pump in heating.

Acknowledgment

This work was supported by the Science and Technology Project in Henan Province (202102310230) and Fundamental Research Funds of Zhongyuan University of Technology (K2019YY013)

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Paper submitted: August 23, 2021
Paper revised: July 18, 2022
Paper accepted: July 18, 2022