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Novel Cascade Solution of Ultra-temperature Industrial Heat Pump System With Multiple Functions

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Abstract

Industrial Heat Pump (IHP) is widely leveraged to gain more economic benefits instead of boilers and electric heating. The process demands of high temperature above 80°C, such as chemical separation-rectification and lithium battery coating, are significantly increasing. Under such conditions, operating stability, system capability and efficiency are all technical difficulties. Therefore, to satisfy the industrial requirement and overcome the difficulties, this paper will provide an integrated cascade solution, including system design, component selection and control strategy, to obtain about 30kW heating capacity with 100°C ~ 120°C air stably. By method of simulation and prototyping test, enhanced vapor injection (EVI), heat recovery and valve cooling technology are well applied to guarantee high efficiency and system reliability, achieving an excellent applicability based on current component condition. In the meantime, not only ultra-temperature air function, space cooling function or medium cold source can be also acquired by evaporating side of MT circuit.

Keywords: Cascade; IHP; EVI; Ultra-temperature ;

1. Introduction

As is shown in Table 1, the heat source above 100 °C is in great demand in industry application, such as the coating process of Lithium battery, PCB board drying, rubber fluid making, etc. The medium is mainly hot wind and steam. Currently the heat source above 100°C is usually achieved by electric heating, coal & gas burning. On the one hand, these methods consume a lot of energy and the waste heat is difficult to be recovered. On the other hand, the pollution is quite serious. Therefore, Heat pump system attracts a lot of attention due to its high efficiency and environmental friendliness and is now widely applied in many occasions.

However, there are still many challenges in IHP, such as high inlet temperature of expansion valve and low system efficiency. The required condensing temperature is higher than 100 °C in IHP. If the hot air temperature needs to be 125 °C, the condensing temperature will reach up to 130~135 °C. So the cascade system is a common system type for such high pressure ratio applications, which is shown in Fig. 1(a). Assume the system subcooling degree is 5°C, so the temperature before the throttle valve will be about 130 °C. There are very few high temperature resistant EXVs in the market. One implementation is as shown in Fig. 1(b). The high-temperature (HT) cycle is enhanced vapor injection cycle which induces a higher efficiency and a lower liquid refrigerant temperature before EXV compared with non-injection cycle. The HT and LT pressure-enthalpy diagrams are shown in Fig. 1(c) and Fig. 1(d), respectively. Taking the condition of HT stage into calculation, the result of the saturation temperature of injection (SIT) is about 103 °C. Assume that the heat exchange temperature difference between SIT and point b is 5 K, the liquid temperature before EXV is 108 °C, which is still beyond most EXV product available range. This is a big challenge to the reliability of the EXV. Long-term operation at high temperatures may lead to demagnetization failure and bidirectional performance attenuation caused by non-metallic seal failure, so more solutions are necessary for ultra-temperature application.

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Accordingly, in order to achieve air supply at 120°C stably and reliably, this paper presents an integrated solution of ultra-temperature IHP system with novel cascade structure. This solution can also recovery some special air condition function to take full advantage of heat source and to improve the system efficiency.

Table 1. Temperature proportion of required heat source [1]

Industry	<100 °C	100-150 °C	150-183 °C	>183 °C
Food and tobacco	2.5	62.5	16.6	18.4
Fiber	0.4	50.3	49.3	0.0
Wood	1.1	9.3	6.6	83.0
Paper pulp	0.0	85.9	4.1	0.0
Chemical	4.8	26.9	50.0	18.3
Rubber	0.0	26.3	53.4	20.4
Leatherware	0.0	100.0	0.0	0.0
Ceramics	0.0	85.6	14.4	0.0

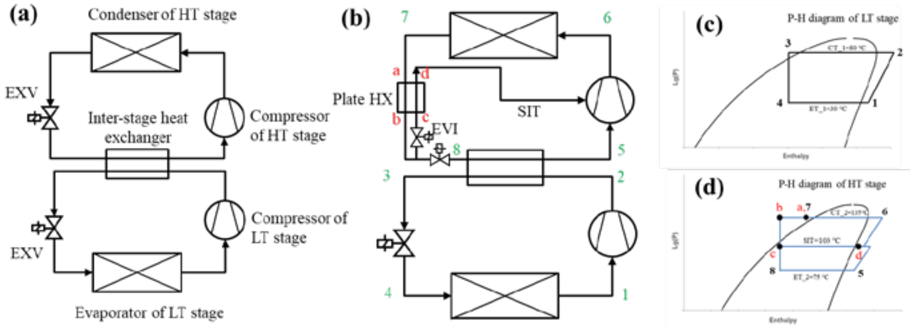


Fig.1 Ordinary Industrial Heat Pump
(a) Typical cascade system (b) cascade system with HT EVI (c) LT p-h diagram (d) HT p-h diagram

2. Solution and Prototyping

2.1. System Design

This novel cascade system is designed for two functions. One is to obtain stable hot air supply at 120°C, which applies EVI technology and valve inlet temperature cooling technology. The other function is designed to expand multiple capability of air conditioning, providing cold water at 7°C for space cooling.

Fig. 2 shows the layout of ultra-temperature industrial heat pump system. The system can be divided into three parts, LT cycle, HT cycle and hot air chamber. The LT cycle is a simple loop with R410A refrigerant. The compressor is variable speed model of Emerson ZWW050. The evaporator is plate heat exchanger (HX) and the design inlet water is air conditioning return water at 12°C. The HT cycle refrigerant is R245fa. Two EVI fix-speed compressors of high temperature heating compressor model are designed in parallel. This compressor model is developed by Emerson and specialized for high-temperature IHP application. With the enhanced design of motor cooling, lubrication system, and new high-temperature resistant materials, a special operation envelope of IHP compressor in Fig. 3 is achievable. Compared with conventional compressors, the evaporating and condensing temperature is significantly higher.

The designed condensing temperature of HT cycle is 125 °C. Hence, two-stage cooling structure of valve inlet temperature is designed. After the HT condenser, the refrigerant flows into two economizers, and then into the valve cooling plate heat exchanger, which path is shown by points (1 – 2 – 3). At this time, the fluid is divided into three branches. The main one (3 – 7 – 8 – 9) flows into HT EXV and condensing-evaporator with majority of refrigerant to guarantee enough heat exchange with LT cycle. The second one (3 – 5 – 6 – 9) is that the refrigerant passed through the evaporation side of the valve cooling plate heat exchanger after being throttled by EXV1, and then goes back to the accumulator. The third one (3 – 4 – 10/10’) flows into two EVI EXVs (EXV2 and EXV3). Then after the evaporation side of two economizers, the refrigerant is injected into two EVI compressors. With this two-stage valve inlet cooling and EVI structure, all the valve inlet temperature can be successfully controlled below 85 °C.

It is necessary that two parallel economizers connect two compressors, respectively. The main reason is EVI control logic related. When the compressor discharge temperature is below 140 °C, EVI EXV controls the injection superheat. If the compressor discharge temperature exceeds 140 °C, the EVI EXV will turn to expand opening to decrease the discharge temperature in higher priority although some liquid will be injected into compressor. In order to deal with this situation, two economizers can control two compressors, respectively. Once stepping into this logic only with one economizer, liquid has to be injected although one compressor's discharge temperature doesn't exceed limitation value. What's more, using one economizer may be not able to distribute liquid refrigerant evenly into two compressors, resulting that one compressor cannot obtain enough effects, while the other gets too much liquid.

Another water loop for heat recovery in hot air chamber is mainly designed for the pre-heating and pre-cooling function of inlet air (designed temperature at 27 °C) to improve the capability and efficiency. The re-cooling heat exchanger is just equipped for prototyping in Fig. 4 to ensure that the outlet air temperature is in safe operation. Fig. 4 also shows the internal structure of the prototyping and the designed temperatures in hot air chamber. The internal heat recovery loop can heat the inlet air up to 65 °C and cool the outlet air down to 83 °C. In the real field applications, this function can also be transferred into waste heat recovery of other heat source.

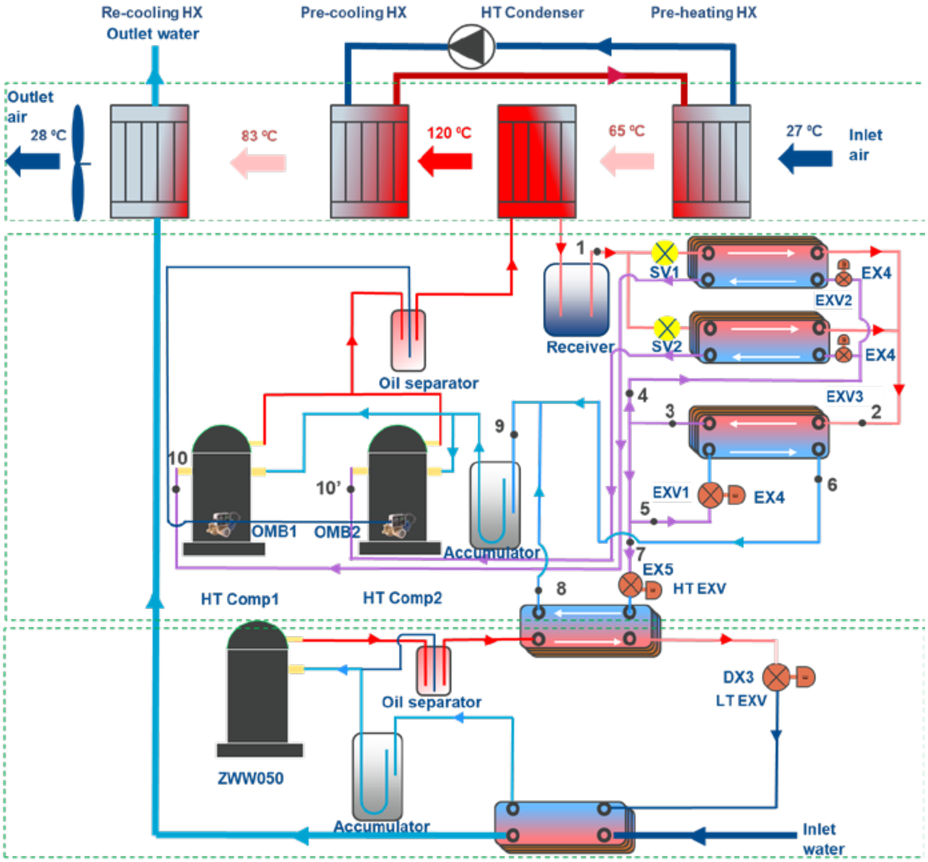


Fig. 2 Ultra-temperature Industrial Heat Pump System Layout

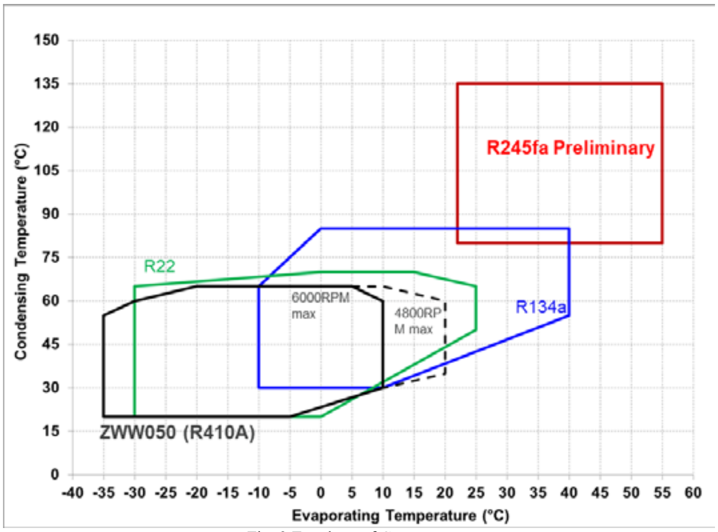


Fig. 3 Envelope of Compressors

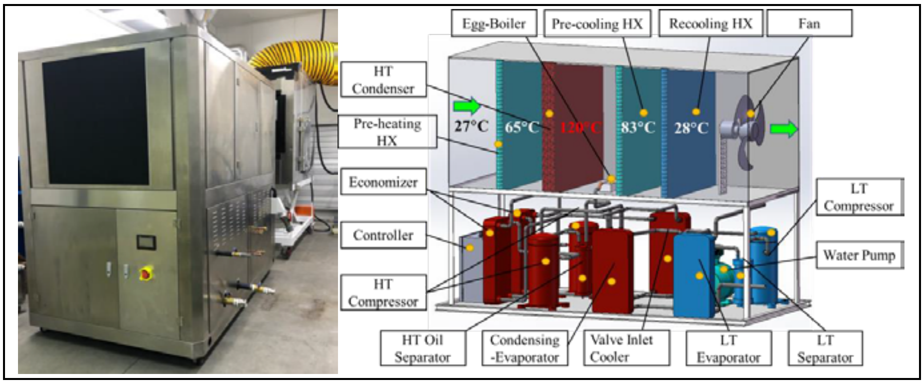


Fig. 4 Prototype and Internal Design

2.2. Control Method

It is a challenge for the reliability of control logic in such a system with multiple EXVs and variable speed compressor. There are five EXVs in this layout, LT EXV, HT EXV, EXV1, EXV2, EXV3. LT EXV is the throttling component of LT cycle, and the PID control target is the LT suction superheat at 6°C. HT EXV is the throttling valve of HT cycle with the PID control target of HT suction superheat at 8°C. EXV2 and EXV3 are the injection throttling valves with PID control target of the injection superheat at 10°C.Owing that there are four EXVs in parallel connection in HT stage, mutual interference will exist. To ensure stable system operation, EXV1 is selected to accommodate the disturbance caused by the other expansion valves because it mainly ensures cooling in front of the valve and has low control accuracy and speed requirements. Considering the cooling effect and the impact on the stability of the system operation, the opening of the cooler valve is limited, and the control method will adopt range control. The LT compressor speed is controlled by cascade adjustment. In order to avoid the delayed effect of the heat capacity of the heat recovery loop on the supply air temperature change, the outer loop PID controller with cascade control targets the HT condensing temperature, and outputs the set value of the low temperature condensing temperature. And the inner loop PID controller outputs the speed of LT compressor. Thus, the most difficult control problem is solved.

In addition, many system protection strategies are adopted, such as discharge temperature, pressure limitation, oil return, etc., are also taken into consideration.

A positive oil return loop with OMB is set to ensure the system oil balance. OMB is an oil management device to be equipped in the position of compressor oil sump. When the oil level is lower than standard level, the solenoid valve will be open to return the oil from oil separator under the action of pressure difference, until the oil level returns to normal. If the oil level lasts decreasing and exceed the upper limitation, alarm occurs, and the system will be shut down for protection. The control logic is achieved through programmable controller. And the electric control cabinet of prototyping is shown in Fig. 5.

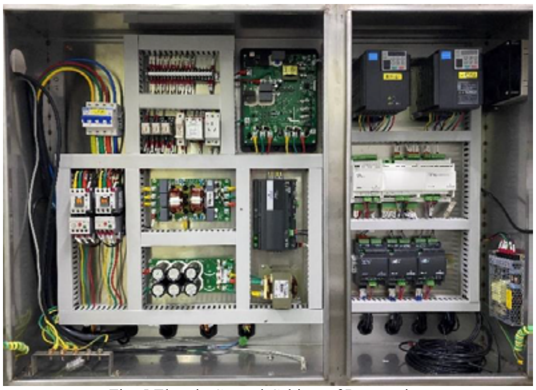


Fig. 5 Electric Control Cabinet of Prototyping

3. Test and Results Analysis

3.1. Test Conditions

Fig. 6 displays the system running envelop of the novel cascade IHP. Considering application environment and system reliability, the ambient temperature and water inlet temperature range are 15 ~ 30°C and 10 ~ 30 °C, respectively. If the water temperature is below 10°C, the risk of freezing will significantly increase. And if the water temperature is above 30 °C, LT evaporating temperature will exceed the upper limitation.

Accordingly, steady and transient performance tests were carried out with the prototyping mentioned above. And the test conditions are shown in Table 2. The rated condition is aiming to validate the IHP performance. The extreme conditions are mainly designed for system stability and reliability validation. All the steady state needs to be maintained over four hours.

3.2. Performance

Table 3 shows the comparison result of prototyping test validation and simulation in the rated condition. The feasibility of the concept can be seen that the test data and the simulation results match very well both in system performance and the operation parameters of LT stage and HT stage, respectively.

Focusing on the performance results, the hot air temperature perfectly exceeds 120°C in this rated condition, leading to enough capability of satisfying the demands of ultra-temperature application. The HT EXV inlet temperature is also successfully controlled below 85°C, which helps to guarantee the reliability of EXV under high temperature working environments. The multiple function of this IHP system is presented by the leaving water temperature. Although there exists a small difference between the simulation results, the leaving water temperature is still enough to carry part of cooling load. It means no energy will be wasted. Finally, the heating COP can reach up to 1.74, which will cause much benefit to replace boilers and electric heaters. Furthermore, taking cooling capacity of LT cycle for space cooling, the system total COP can even reach 2.83.

Table 2. Test Conditions

No.	Condition	Ambient Temperature	Water Inlet Temperature	Water Flow Rate	Target Air Temperature
		°C	°C	m3/h	°C
1	Rated Point	27	12	2	120
2		15	10	2	Above 100
3	Extreme Point	30	10	2	120
4		30	30	2	120

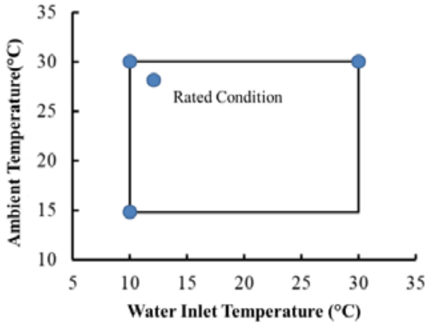


Fig. 6 System Running Envelop

Table 3. Comparisons between test validation and simulation design

Items		Test Validation Results	Design and Simulation Results
System Performance	Inlet Air Temperature	27 °C	27 °C
	Inlet Water Temperature	12 °C	12 °C
	Hot Air Temperature	121.6 °C	120 °C
	HT EXV Inlet Temperature	80.8 °C	70~85 °C
	Leaving Water Temperature	7.8 °C	7 °C
	Heating Capacity	29.7 kW	31.2 kW
	Total Compressor Power	17.1 kW	18.0 kW
	Heating COP	1.74	1.73
LT stage	Suction Saturation Temp.	2.6 °C	1.3 °C
	Discharge Saturation Temp.	54.7 °C	52.7 °C
	Suction Superheat	4.0 K	4.0 K
HT stage	Suction Saturation Temp.	49.7 °C	47.7 °C
	Injection Saturation Temp.	93.3 °C	86.2 °C
	Discharge Saturation Temp.	123.2 °C	124.8 °C
	Suction Superheat	11.0 K	11.0 K
	Injection Superheat	10.3 K	10.3 K

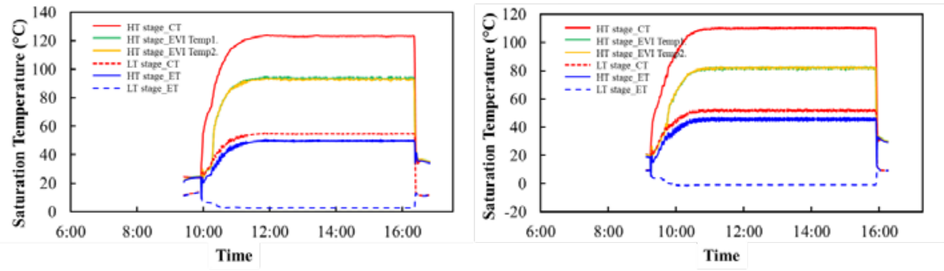
3.3. Transitional Behavior and Discussion

Fig. 7 displays an excellent result of the system dynamic characteristics. All the four conditions perform a stable running process from startup to steady operation. The hot air temperatures are 121.6°C, 103.2°C, 119.4°C and 120.2°C, respectively. In fact, No.3 condition is the worst condition for IHP and will rarely occur. Although the heating capacity has attenuation, the target air temperature is still higher than 100°C.

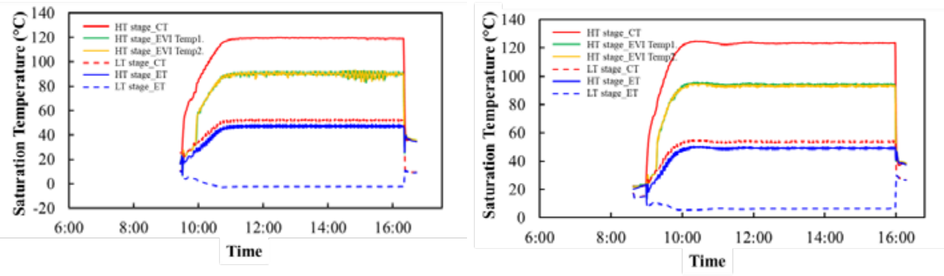
Compared with Fig. 7(c) and 7(d), when the water temperature decreases, it will take longer time to get to the steady state. When the water temperature is 10°C, the LT evaporating temperature is nearly below 0°C, increasing the freezing risk. And also, the capacity of LT stage is too small to induce a lower HT evaporating temperature.

The whole system is in interior relation and needs a balance adjustment control. For instance, if there are problems in the HT EXVs control method, the refrigerant distribution will cause big trouble. Once too little refrigerant flows into the condensing-evaporator, the LT condensing temperature will be too high duo to the lack of heat exchange. Or too much refrigerant flows into the condensing-evaporator, it means that too little fluid can be used to cool the valve inlet temperature.

Hence, the control logic is very crucial to obtain a good performance and reliability and has been solved in this study.



(a) Rated Condition (A27/W12) (b) Extreme Condition (A15/W10)



(c) Extreme Condition (A30/W10) (d) Extreme Condition (A30/W30)

Fig. 7 Test results of transient system performances

4. Conclusion

This study focuses on the performance and reliability of the novel cascade solution of ultra-temperature industrial heat pump. The EXV temperature resistance problem is solved by the design of economizer and valve inlet cooler, and the inlet temperature is controlled below 85°C. In this system, other technologies, such as OMB oil return, heat recovery loop and EVI technology, are also optimized to improve the efficiency and stability. In addition, the advanced control method is discussed and succeed to achieve the hot air temperature up to 120°C in an internal balanced state. In the future, the study on new refrigerant substitution can be developed.

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