EXPERIMENTAL STUDY ON REFRIGERATION SYSTEM'S PERFORMANCE OF THE REFRIGERATOR TRUCK USING R404A REFRIGERANT

by

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A refrigerated system experimental bench using R404A as the refrigerant was built to address the current issues of high compressor discharge temperature and poor refrigeration performance of refrigerated systems for cold storage. The effects of compressor speed and temperature changes within the storage on the main refrigeration performance parameters of the system were studied and analyzed. The results show that when the rotational speed is increased from 2500-4500 rpm under the conditions of 32 °C outside and 0 °C inside, the highest system exhaust temperature is 84.3 °C, which is lower than 90 °C, and the maximum system COP is 3.86, and when the compressor speed is increased from 3500 rpm under the conditions of –5 °C to 5 °C, the system exhaust temperature is lower than 90 °C. The COP can reach 2.74, especially at –5 °C.

Key words: *refrigerated truck, refrigeration system, R404A refrigerant, refrigeration performance*

Introduction

The standard of living for citizens has increased as the nation economy has grown. Fresh ingredients, energy efficiency, and environmental protection are becoming more popular, especially when it comes to the low temperature storage and delivery of goods in the food, pharmaceutical, and chemical industries, which urgently require energy-saving and environmentally friendly cold chain systems [1]. However, cold storage is a big energy user and electricity is a significant component of its operational costs [2]. As one of the crucial infrastructures for cold chain logistics operations, demand for cold storage is also rising. The development of the cold storage refrigeration business is severely hampered by the current system low refrigeration performance and high exhaust temperature.

Some specialists and academics in the field have performed research to find ways to improve refrigeration performance while lowering the energy consumption of cold storage systems. Elbel *et al*. [3] experimentally analyzed the performance of a make-up circuit system with a flash evaporator and discovered that the system cooling capacity was 7% higher than that of a traditional refrigeration system. Wang *et al*. [4] designed a quasi-two-stage compression cycle refrigeration system for temperature extremes and concluded that the cooling capacity and COP of the quasi-two-stage compression system were increased by 14% and 4%,

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respectively, compared to the normal system at the high temperature operating condition of 46.1 °C. Cui *et al*. [5] conducted an experimental study on the performance of a refrigeration system using gas make-up technology, and the results showed that the modified system can effectively improve the system cooling efficiency under low temperature conditions and the system operation is relatively stable. Xu *et al*. [6] conducted an experimental comparison of three different fin types of micro-channel heat exchangers and concluded that the capacity of heat exchangers with new fins and corrugated fins with drainage design was 56.7% and 25.8% higher than the capacity of louvered fin type heat exchangers under wet conditions, respectively. Kwon *et al*. [7] simulated the single-phase heat transfer of a compact cross-flow micro-channel heat exchanger and found that the maximum power density of the heat exchanger was 60 W/cm^3 for air inlet temperature and circulating mass inlet temperature of 27 °C and 80 °C, respectively. Ning *et al*. [8] conducted an experimental study on the performance of three stacked refrigeration systems, NH_3/CO_2, R290/CO_2, and R404A/CO_2, and concluded that the NH_3/CO_2 stacked refrigeration system has the largest COP. Zhang *et al*. [9] experimentally studied a vapor injection quasi-two-stage compression refrigeration system and found that the injection coefficient and the system cooling capacity gradually decreased with the increase of the mixed fluid outlet pressure, while the COP first increased and then decreased. Dong *et al*. [10] experimentally studied the effect of compressor frequency on the performance of rotating cooling type cold storage, and the experiment provided a theoretical basis for the selection of compressor frequency corresponding to the realization of rotating cooling between multiple cold rooms with the same temperature under different working conditions. Wu *et al*. [11] developed a solar jet/compression combined refrigeration cycle system, which improved the electric power performance factor by about 31.5% compared to a single compression refrigeration cycle under the same operating conditions for all-day operation on weekdays. Xiong *et al*. [12] analyzed the factors influencing the two-phase flow distribution of micro-channel heat exchangers in refrigeration systems and concluded that the phase separation technique to separate the two-phase flow of gas or liquid in the heat exchanger can effectively improve the heat transfer effect of micro-channel heat exchangers. By comparing and analyzing five refrigerants R410A, R32, R290, R134a, and R404A applied in refrigeration systems, Luo [13] found that the system based on R404A has better cooling performance. He *et al*. [14] studied refrigeration performance of a combined magnetic refrigeration system. Mohanraj *et al*. [15] applied the artificial neural networks to refrigeration systems. The convolutional neural networks [16-19], the deep learning technique [20] and the diffusion tensor imaging [21, 22] are also the promising candidates for analysis of the refrigeration systems in future.

The present study on refrigeration performance includes mainly three aspects, *i.e.*, gas make-up technology, micro-channel heat exchanger structure, and refrigeration cycle work gases. The performance of cold storage refrigeration system can be significantly improved by the application of gas make-up technology and micro-channel heat exchanger. In this paper, based on the gas replenishment technology, R404A is used as the refrigerant cycle, and the micro-channel parallel flow heat exchanger is used for the heat exchanger both inside and outside the storage, and the experimental bench is built for analysis of the performance of the refrigeration system, and the influence of the compressor speed and the change of the temperature inside the storage on the refrigeration performance of the system is studied experimentally.

Experimental set-up and method

Experimental set-up

The experiments were conducted in a standard enthalpy difference laboratory, with the outdoor side simulating the outside environment and the indoor side simulating the inside environment, where the dry bulb temperature control range of the indoor environment was –25~50 ℃ and the wet bulb temperature control range was –21~45 ℃, while the dry bulb temperature control range of the outdoor environment was –30~55 ℃ and the wet bulb temperature control range was –25~50 ℃, with a temperature control accuracy of ±0.2 ℃. Refrigeration system test bench mainly includes refrigerant circulation system, air circulation system and measurement control system. The main parameters of the test system equipment are shown in tab. 1.

Table 1. System main equipment parameters

Equipment name	Model and parameters	Unit	Quantity
Scroll compressors	Panasonic 3CC171SA0M, applicable work material R404A, exhaust volume 171.2 cm^3/rec, rated cooling capacity 29.9 kW	Each	1
Heat exchanger in the library	Parallel flow heat exchanger, heat transfer area 5.31 m^2, number of flat tubes 74 (1:2)	Each	1
Heat exchanger outside the library	Parallel flow heat exchanger, heat transfer area 5.70 m^2, number of flat tubes 76 (1:2)	Each	1
Intermediate heat exchangers	Plate heat exchanger, Vantage B3-026-16D, with a heat exchange area of 0.364 m^2	Each	1
Heat exchanger side fan in the library	Ebm K3G097 inverter centrifugal fans, each with a maximum rated air capacity of 1200 m^3 per hour	Each	6
Heat exchanger side fan outside the warehouse	Ebm inverter axial flow fans, each with a maximum rated air volume of 2200 m^3 per hour	Each	5
Main circuit expansion valve	Carle electronic expansion valve E2V-24, rated capacity 26.1 kW. Adjustment range: 10~100%	Set	1
Supplementary circuit expansion valve	Carle electronic expansion valve E2V-11, rated capacity 9.2 kW. Adjustment range: 10~100%	Set	1
Electronic Breezometer	EY3-2A electronic breeze meter, measuring range: 0~30 m/s, error range: ±0.2%	Piece	1
Power meter	Qingdao Qingzhi ZW3414D power meter, measurement accuracy: ≤ ±0.4%	Piece	1
Pressure sensors	PT5-30M/T and PT5-07M/T, measurement accuracy: ≤ ±1%FS	Piece	6
Temperature sensor	T-type, measurement accuracy: ≤ ±0.5 ℃	Piece	9
Data collector	Agilent34972A	Set	2

The design of refrigeration system is based on the principle of quasi-two-stage compression cycle, quasi-two-stage compression is to add a charge air circuit to the compressor can be a good way to solve the problems of large pressure ratio and high exhaust temperature encountered in single-stage compression. The concrete method is: in the quasi-two-stage compression refrigerating system, the refrigerant after condensing and heat exchange in the main road electronic expansion valve, a small part of the refrigerant through the electronic expansion valve, into the intermediate heat exchanger, and the refrigerant from the condenser heat exchange, increase the main road refrigerant subcooling degree, and the finally, the makeup refrigerant is mixed with the main refrigerant at the low pressure inlet of the compressor, reducing the exhaust temperature of the compressor. The refrigeration cycle of the cold storage refrigeration system is illustrated in fig. 1, respectively.

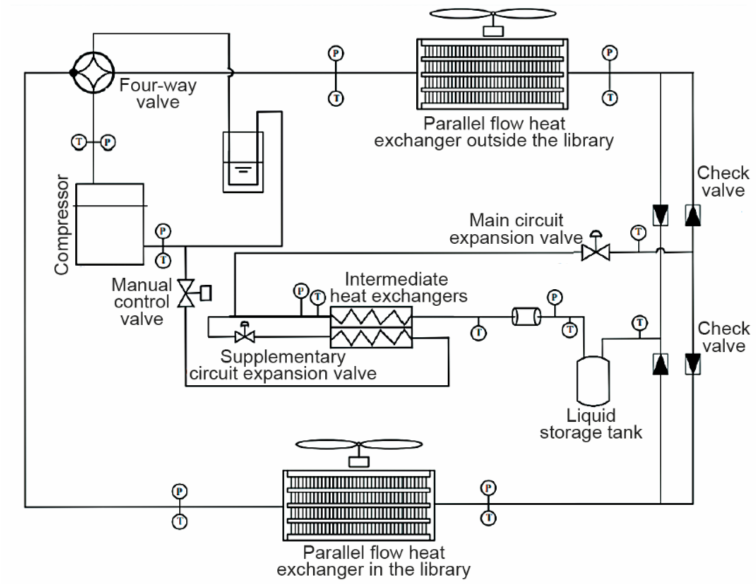

Figure 1. Refrigeration system refrigeration cycle and measurement point location arrangement

Experimental working conditions

Referring to GBT-24616-2019 *refrigeration, frozen food logistics packaging, marking, transportation and storage*, GB/50072-2010 *cold storage design specifications*, GB/T30134-2013 *cold storage management specifications* GB/T25129-2010 *air cooler for refrigeration*, JB/T11967-2014 *refrigeration and air conditioning equipment 30 ℃*; ultra-low temperature cold storage design temperature is generally –30 ℃ ~ –80 ℃. According to the design temperature of high temperature cold storage selected refrigerated experimental conditions, and in order to explore the performance of the system in the refrigerated –5 ℃ operation, so the refrigerated experimental conditions selected for –5 ℃ ~ +5 ℃. In the test, the superheat setting of the main expansion valve is 5 ℃, the superheat setting of the supplementary expansion valve is 30 ℃, the air volume of the fan inside the store is 7200 m³ per hour, and the air volume of the fan outside the store is 11000 m³ per hour. The experimental working parameters are shown in tab. 2.

Table 2. Experimental working situation

Test conditions	Environment outside the warehouse		Environment in the warehouse		Compressor rotation speed
	Dry bulb temperature	Wet bulb temperature	Dry bulb temperature	Relative humidity	
Variable compressor Rotational speed	32 °C	24 °C	0 °C	60%	2500 rpm
					3000 rpm
					3500 rpm
					4000 rpm
					4500 rpm
Variable storage temperature	32 °C	24 °C	–5 °C	60%	3500 rpm
			–2 °C		
			3 °C		
			5 °C		

Experimental data treatment

The temperature and pressure of each measurement point of the system can be measured and automatically recorded through thermocouples and pressure sensors. The inside of the library has an air volume measurement box, which can measure parameters such as evaporator air volume and temperature, and the compressor power is measured through an electricity meter. Refrigeration capacity and COP calculation formula is:

$$Q_c = q_m (h_{evap,out} - h_{evap,in}) \tag{1}$$

$$COP_c = \frac{Q_c}{P} \tag{2}$$

where Q_c is the evaporator heating capacity, q_m [kgs^{-1}] – the refrigerant mass-flow rate of evaporator, $h_{evap,out}$ [kJkg^{-1}] – the refrigerant enthalpy of evaporator outlet, $h_{evap,in}$ [kJkg^{-1}] – the refrigerant enthalpy of evaporator inlet, and P [kW] – compressor power consumption.

Analysis of the results

Compressor speed on refrigeration system cooling properties

Figure 2 displays the effect of compressor speed variation on the system exhaust temperature, and it can be seen from the figure that as the compressor speed rises, the exhaust temperature rises. Because when the system starts to run for 3 minutes, the system parallel flow evaporator starts to travel frost phenomenon, and as the speed increases, the faster the frosting rate. When the speed increases from 2500 rpm to 4500 rpm, the exhaust temperature increases by 15.4%. And the highest system exhaust temperature is 84.3 °C, lower than 90 °C, which ensures the smooth operation of the compressor.

Figure 3 shows the effect of compressor speed variation on the system cooling capacity, and it can be seen from the figure that as the compressor speed increases, the cooling capacity increases. When the speed increases from 2500 rpm to 4500 rpm, the cooling capacity increases from 14.25 kW to 18.83 kW, an increase of 32.1%.

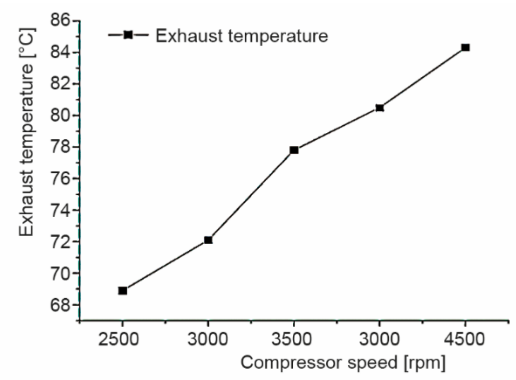

Figure 2. Effect of compressor speed on exhaust capacity

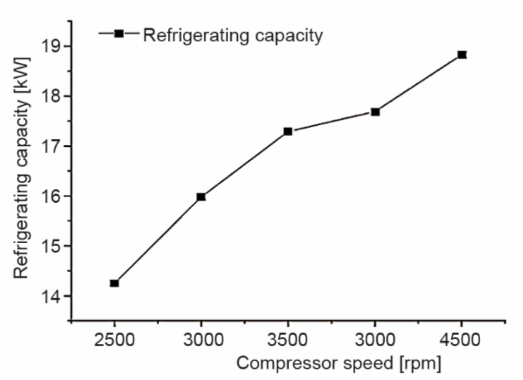

Figure 3. Effect of compressor speed on refrigerating temperature

Figure 4 illustrates the effects of compressor speed variation on compressor power, which shows that compressor power goes up as the compressor speed increases. When the speed increases from 2500 rpm to 4500 rpm, the compressor power increases from 3.93 kW to 5.29 kW, an increase of 34.6%.

Figure 5 shows the effect of compressor speed change on the system COP, from the figure, it can be seen that the system COP increases and then decreases with the increase of compressor speed. When the speed increases from 2500 rpm to 3500 rpm, the COP increases from 3.62 to 3.86. When the speed increases from 3500 rpm to 4500 rpm, the COP decreases from 3.86 to 3.58.

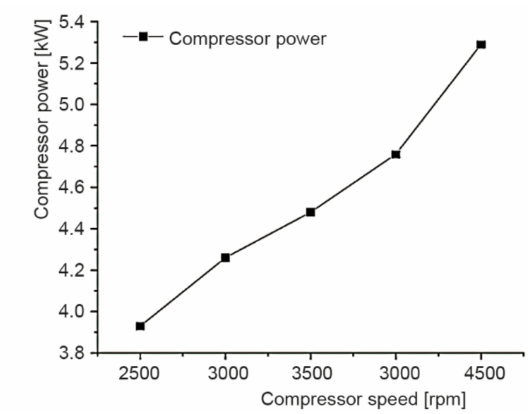

Figure 4. Effect of compressor speed on compressor power

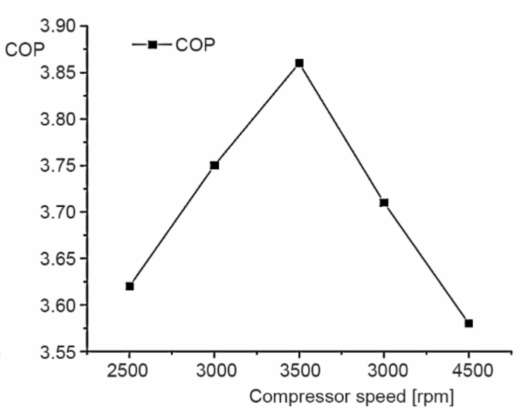

Figure 5. Effect of compressor speed on system COP

The effect of temperature in the library on the refrigeration capacity of the refrigeration system

Figure 6 demonstrates the effect of the temperature change inside the reservoir on the system exhaust temperature. As can be seen from the figure, as the temperature inside the reservoir increases, the system exhaust temperature drops. When the temperature inside the reservoir increases from –5 °C to 5 °C, the exhaust temperature decreases by 17.4 °C.

Figure 7 demonstrates the effect of the temperature change in the storage on the system cooling capacity, and it can be seen from the figure that as the temperature in the storage increases, the system cooling capacity increases. The system cooling capacity increases from 9.56 kW to 21.88 kW when the temperature inside the storage increases from –5 °C to 5 °C, an increase of 56.3%.

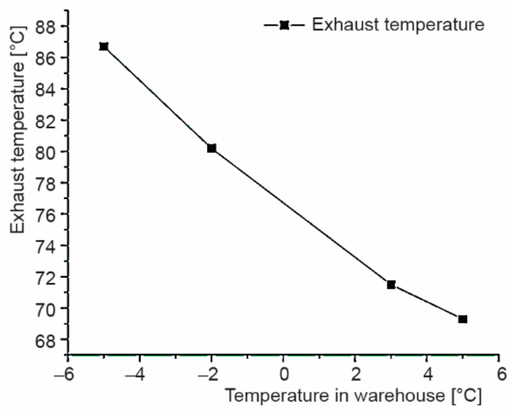

Figure 6. Effect of temperature in the library on exhaust temperature

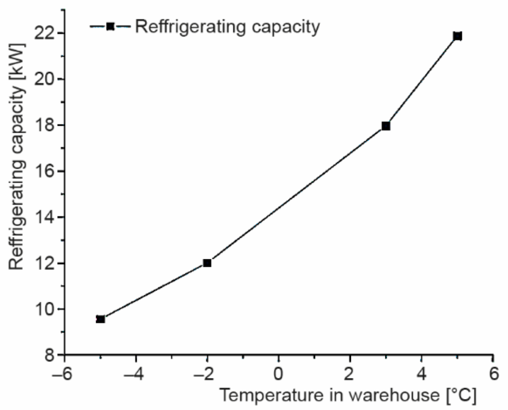

Figure 7. The effect of temperature on refrigerating capacity

Figure 8 shows the effect of temperature change in the storage on the system compressor power, and it can be seen from the figure that as the storage temperature increases, the system compressor power increases. The system compressor power increases from 3.49 kW to 5.48 kW when the temperature inside the storage increases from –5 ℃ to 5 ℃, an increase of 36.3%.

Figure 9 presents the effect of temperature variation in the reservoir on the system COP, and it can be seen from the figure that as the temperature in the reservoir increases, the system COP increases. When the temperature inside the reservoir increases from –5 °C to 5 °C, the system COP increases from 2.74 to 3.99, an increase of 31.3%.

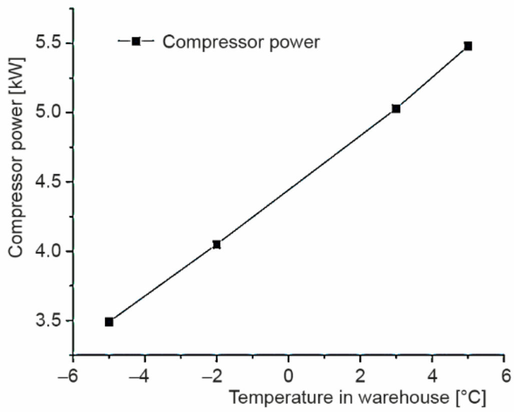

Figure 8. The effect of temperature in the storehouse on the power of the compressor

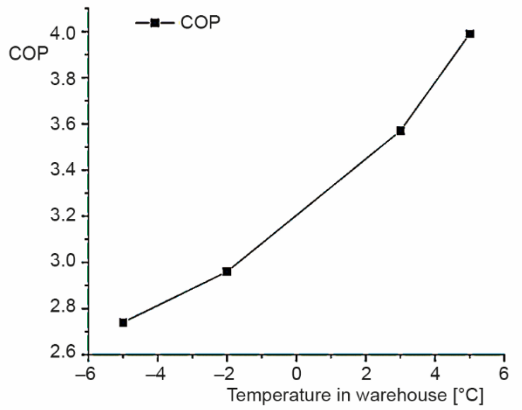

Figure 9. Effect of temperature in the library on COP

Conclusions

On the basis of gas replenishment technology, the experimental bench of R404A type refrigeration system was built to testing the influence of compressor speed and temperature changes in the storage on the main performance parameters of the refrigeration system, and the main conclusions are as follows.

- Outside the library 32 ℃, the library 0 ℃ working conditions, when the speed is increased from 2500 rpm to 4500 rpm, the highest system exhaust temperature is 84.3 ℃, lower than 90 ℃, the maximum system COP can reach 3.86; and in the compressor speed 3500 rpm, when the temperature inside the library from –5 ℃ to 5 ℃, the system exhaust temperature are lower than 90 ℃, especially in COP can reach 2.74 at –5 ℃.
- In the evaporator frost occurs, the gas replenishment technology can ensure that the system runs steadily at high speed, and the compressor runs at high speed to improve the refrigeration capacity, in a certain working condition can meet the demand for cold storage refrigeration capacity, but the pursuit of high speed can lead to a reduction in refrigeration system cooling efficiency.

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