EFFECT OF SUPERHEAT ON REFRIGERATION SYSTEM PERFORMANCE OF REFRIGERATED TRUCK

by

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According to the characteristics of variable operating conditions and high exhaust temperature of the refrigeration system of the refrigerator truck, the change of the superheat at the outlet of the evaporator is adjusted by a new electronic expansion valve, and a performance test-bed using the R404A refrigerant is built to study the influence of the superheat at the outlet of the evaporator on the performance of the refrigeration system of the refrigerator truck. The results show that in the process of increasing the superheat at the outlet of the evaporator, the outlet temperature of the evaporator increases and the evaporation temperature decrease, the cooling capacity of the system is reduced by 8.4%, and the COP of the system increases first and then decreases; At this time, the optimal superheat at the evaporator outlet is 6 ℃, and the system COP reaches the optimal value of 2.856.

Key words: *refrigerated truck, refrigeration system, evaporator, superheat*

Introduction

A pure electric refrigerated vehicle has the advantages in energy saving and environment protecting, so it is in line with the development strategy for the carbon neutralization and the peak CO_2 emission in China for energy saving and emission reduction, and has been widely used in the cold chain logistics industry [1]. The superheat of evaporator outlet plays an important role in ensuring the stable and efficient operation of the refrigeration system of the refrigerated truck. Regulating the mass-flow of working medium by controlling the superheat of the evaporator outlet is an effective means to improve the refrigeration performance of the refrigerated truck. However, the two-phase region of the working medium inside the evaporator sometimes changes greatly, which promotes the refrigeration capacity of the evaporator, because the superheat of the working medium at the outlet of the evaporator is reduced. The compressor liquid strike can only be prevented by ensuring that the overheated refrigerant gas passes through the evaporator outlet. At the same time, in order to reduce the system exhaust superheat, prolong the service life of lubricating oil, and ensure the smooth operation of the system, it is necessary to ensure that the evaporator outlet superheat cannot be too high [2, 3]. Therefore, it is of great significance to study and analyze the influence of the optimal superheat of evaporator outlet on the refrigeration performance of refrigerated truck.

Some scholars have studied the effect of outlet superheat of evaporator on the performance of single device or system of evaporator. Beghi *et al*. [4] established the superheat

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control knowledge base suitable for refrigeration system. Wang *et al.* [5] studied the influence of superheat on the heating performance of the vehicular CO_2 heat pump system in cold areas through experiments, and found that the system performance requirements can be met only when the optimal superheat is 6 ℃. Choi *et al.* [6] experimentally studied the heating performance changes of the heat pump system under different electronic expansion valve superheat setting values, and concluded that the heating performance coefficient of the heat pump increased by 13.9% in the process of controlling the superheat from 2 ℃ to 8 ℃. Yan *et al.* [7] obtained the refrigeration performance curve of vehicle heat pump evaporator under the superheat of different evaporator outlet working medium, and found that when the superheat was increased, the cooling capacity of the system increased, and the COP increased first and then decreased. Yu *et al.* [8] experimentally studied the variation of evaporator cooling capacity of CO_2 heat pump system under different superheat of evaporator outlet working medium, and the results showed that in the process of reducing superheat, the evaporator cooling capacity increased by a maximum of 57.9%. Liang *et al.* [9] conducted a simulation study on the system cooling performance parameters of different refrigerants R22, R134a, and R410A under different outlet superheat, and concluded that with the change of superheat, the system using refrigerant R410A had better performance, and the system cooling capacity was opposite to the change trend of evaporator outlet superheat. Li *et al.* [10] found that when the superheat value of the outlet working medium of the evaporator was 5 ℃, the refrigeration performance of the vehicle heat pump reached the optimum. Zhang *et al.* [11] experimentally studied the mutual influence trend between the superheat and the cooling coefficient COP in the CO_2 heat pump system, and concluded that in the process of increasing the superheat, the cooling coefficient COP of the system increased first and then decreased.

The control strategy of superheat is also a hot topic in current research [12, 13] and nanofluids can be used for enhancing thermal conduction [14-19]. Rapid and accurate regulation of superheat is the premise of improving refrigeration performance, so some scholars conducted corresponding studies on this topic [20-22]. In this paper, a new type of electronic expansion valve is adopted. The temperature of the evaporator outlet is automatically collected by the driver, and the difference between the outlet pressure and the corresponding saturation temperature is the superheat. At the same time, a refrigerated truck refrigeration system performance test bench based on R404A was built to study the influence of evaporator outlet superheat on the performance of refrigerated truck refrigeration system in combination with the characteristics of variable operating conditions and high exhaust temperature of refrigerated truck refrigeration system.

Experimental system

The system circulation principle is shown in fig. 1. The refrigeration system works as follows; the refrigeration cycle is divided into two ways:

- main circulation, which is inherently sequential as the compressor exhaust port, the parallel flow heat exchanger outside the vehicle, the economizer, the main electronic expansion valve, the in-vehicle tubular evaporator, and the compressor suction port,
- and repair cycle, where the sequential connection is as follows: the compressor exhaust port, the parallel flow heat exchanger outside the vehicle, the repair electronic expansion valve, the economic device, and the compressor suction port.

Low pressure air-supply circulation

The principle of the low pressure air-supply circulation is that the high temperature and high pressure refrigerant gas is discharged from the air outlet of the compressor (state 2), and is divided into two ways after the condenser is cooled (state 2-state 5), and the main-way refrigerant is subcooled to the state 3 by the supplementary refrigerant in the economizer, the main expansion valve is throttled to the state 4, and is evaporated in the evaporator (state 4-state 1). The supplementary refrigerants are throttled by the supplementary expansion valve (state 5-state 6), and then enter the economizer for endothermic evaporation (state 6-state 7). The supplementary refrigerants have a small segment of the pipe to throttle before entering the low pressure air-supply inlet (state 7-state 8), the throttled supplementary refrigerants enter the low pressure air-supply inlet and mix with the main refrigerants (state 8-state 9), and the mixed refrigerants are compressed to form the exhaust state 2, so that the cycle is repeated to realize quasi-secondary compression of a single compressor; if the undercooling degree of refrigerants in the air-supply circuit is too high, the state 9 will be shifted to the state 9', and the corresponding state 2 will shift to 2'. Figure 2 shows the theoretical cycle diagram of low pressure air supply.

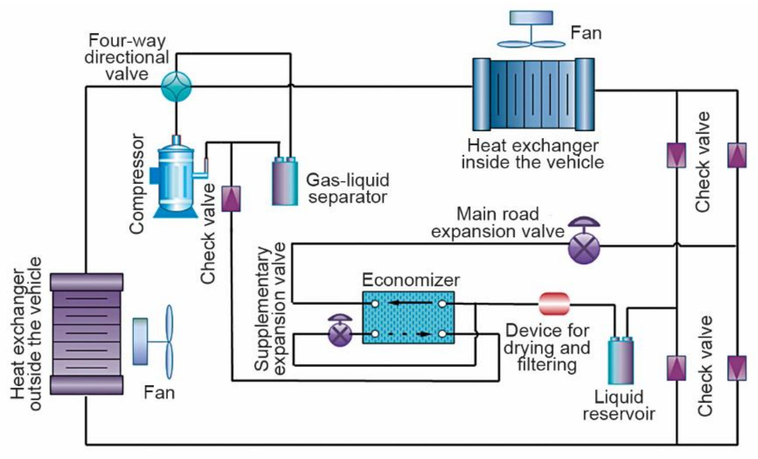

Figure 1. System circulation principle

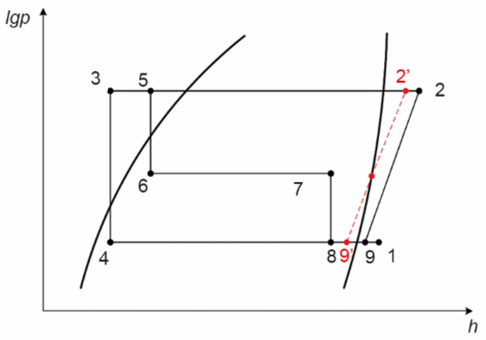

Figure 2. Theoretical circulation of pressure and air replenishment

The thermodynamic cycle formula is as follows:

– Heating capacity of heat pump system on the side of condenser:

$$Q_{\mathrm{h}} = \dot{m}_{\mathrm{r}}(h_2 - h_5)$$

where $\dot{m}_{\mathrm{r}}$ [kgs^{-1}] is the mass-flow rate of compressor exhaust refrigerants, h_2 [kJkg^{-1}] – the enthalpy value of compressor exhaust refrigerants, and h_5 [kJkg^{-1}] – the enthalpy value of refrigerants at condenser outlet.

- Compressor power:

$$W = \dot{m}_\mathrm{r}(h_9 - h_2)$$

where h_2 [kJkg^{-1}] is the enthalpy value of compressor exhaust refrigerants and h_9 [kJkg^{-1}] – the enthalpy value of refrigerants entering compressor suction chamber.

- Refrigerating capacity of heat pump system on the side of evaporator:

$$Q_c = \dot{m}_o(h_1 - h_4)$$

where $\dot{m}_o$ [kgs^{-1}] is the mass-flow rate of refrigerants entering evaporator, h_1 [kJkg^{-1}] – the enthalpy value of refrigerants at evaporator outlet, and h_4 [kJkg^{-1}] – the enthalpy value of refrigerants at the inlet of evaporator.

- Refrigeration coefficient of heat pump system:

$$\mathrm{COP}_c = \frac{Q_c}{W}$$

- Heating coefficient of heat pump system:

$$\mathrm{COP}_\mathrm{h} = \frac{Q_\mathrm{h}}{W} = \frac{W + Q_c}{W} = 1 + \frac{Q_c}{W}$$

- Mass-flow rate of air-supply refrigerants:

$$\dot{m}' = \dot{m}_r - \dot{m}_o$$

- Heat transfer capacity of economizer:

$$Q' = \dot{m}_o(h_5 - h_3)$$

where h_3 [kJkg^{-1}] is the enthalpy value of refrigerants at the outlet of economizer on the side of main cycle and h_5 [kJkg^{-1}] – the enthalpy value of refrigerants at condenser outlet.

- Outlet superheat of the evaporator:

$$T_\mathrm{e,sh} = T_\mathrm{e} - T_\mathrm{e,sat}$$

where T_e [°C] is the evaporation temperature and $T_\mathrm{e,sat}$ [°C] – the saturation temperature corresponding to the outlet pressure of the evaporator

- Overheat of compressor exhaust port:

$$T_\mathrm{c,sh} = T_\mathrm{c} - T_\mathrm{c,sat}$$

where T_c [°C] is the compressor exhaust temperature and $T_\mathrm{c,sat}$ [°C] – the saturation temperature corresponding to the pressure at the compressor exhaust port.

Experimental process

The test platform is built in the enthalpy difference laboratory, and the performance of refrigeration system of refrigerated truck is tested by the method of air enthalpy difference. During the experiment, a temperature sensor and a pressure sensor are, respectively, set on the pipe at the outlet of the evaporator. The temperature and pressure collected by the two sensors are converted into the superheat of the working medium through calculation to further control the opening size of the expansion valve. The compressor used in the experiment is a variable-frequency scroll compressor with intermediate air supply. A single-row two-flow micro-channel parallel flow condenser is used for the external condenser, a tube-fin evaporator is used for the internal evaporator, a variable-frequency axial flow fan is used for the external condensing fan, and a variable-frequency centrifugal fan is used for the internal evaporation fan. Experiments, refrigeration cycle system of temperature and pressure can be by means of the thermocouple temperature measuring point, pressure can be through the pressure measuring point of pressure sensors, temperature and pressure were collected relevant numerical by real-time feedback to the work station, data acquisition instrument and measuring box to collect the car the evaporation of the evaporator fan air volume, The system compressor power is measured and collected by an electrical meter. Data were collected after the changes of the data of the measurement points in the laboratory refrigeration condition and the whole experimental system were stable. After the performance change curve was obtained, the set value of the overheat of the expansion valve was manually adjusted for the next round of experimental data collection. The specification parameters of the main parts are shown in tab. 1, and the physical diagram of the experimental system is shown in fig. 3.

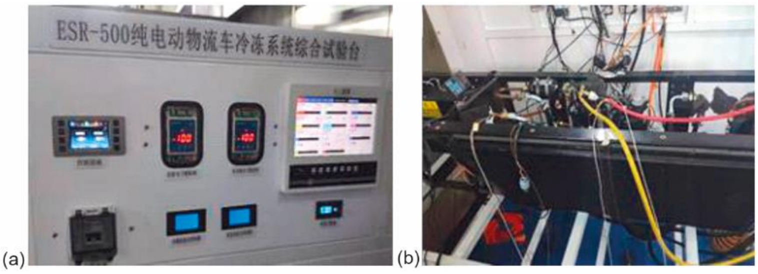

Figure 3. The physical object of test bench

Table 1. The specifications and parameters of main components

Equipment	Type	Characteristic parameter
Compressor	DC variable frequency electric scroll compressor	Displacement 35.6 ml/rev, rotational speed 900~7200 rpm
Outside the heat exchanger	Micro-channel parallel flow heat exchanger	Boundary dimension 940 × 469 × 20 mm, single row and two processes
Inside the heat exchanger	Tube fin heat exchanger	Boundary dimension 1230 × 546 × 195 mm, number of tubes 54, number of processes 3
Outside the wind turbine	Variable frequency axial flow fan	DC26 V, maximum air volume 4000 m^3 per hour
Inside the wind turbine	Variable frequency centrifugal fan	DC26 V, maximum air volume 3000 m^3 per hour
Main circuit electronic expansion valve	R404A applies	Maximum cooling capacity 26.1 kW, opening adjustment range 10~100%
Circuit make-up electronic expansion valve	R404A applies	Maximum cooling capacity 9.2 kW, opening adjustment range 10~100%
Economizer	Sleeve type heat exchanger	Design capacity 6.2 kW, design temperature –160~+200 °C
Four-way reversing valve	R404A applies	Applicable capacity 18~45 kW
Gas liquid separator	R404A applies	Volume 4 L, maximum working pressure 4.5 MPa

According to the relevant national and industrial standards, the experimental conditions of the refrigeration system were established. The refrigerant used in the experiment was R404A, and the optimal charging volume of the system was determined to be 2.9 kg through the charging volume experiment. The experimental conditions are shown in tab. 2.

Table 2. The experimental conditions

Project		Set parameters
Evaporator side	Dry bulb temperature [℃]	0
	Air volume [m^3 per hour]	3000
Condenser side	Dry bulb temperature [℃]	32
	Wet bulb temperature [℃]	24
	Air volume [m^3 per hour]	4000
Compressor	Speed [rpm]	4200

Experimental results and analysis

Figure 4 shows the change curve of the working medium temperature at the outlet of the evaporator as a function of the superheat. It can be seen from fig. 4 that when the superheat is increased, the change curve of the working medium temperature at the outlet of the evaporator shows a slow upward trend. When the superheat is increased from 2 ℃ to 10 ℃, the outlet temperature of the system evaporator increases from –6.56 ℃ to –1.91 ℃, an increase of 4.65 ℃. This is because when improve the degree of superheat evaporator export working medium, import and export of collected on both ends of the evaporator temperature difference value increased from 2.2 ℃ to 7.1 ℃, at the same time because of the evaporator has a pressure difference on both ends of the import and export, to further promote the uniformity of liquid refrigerant inside the evaporator points, improve the internal temperature distribution of each process pipe evaporator, strengthened the evaporator heat transfer effect, The outlet temperature of the evaporator rises accordingly.

Figure 5 shows the change curve of evaporator temperature with superheat. It can be seen from fig. 5 that when the superheat is increased, the change curve of evaporation temper-

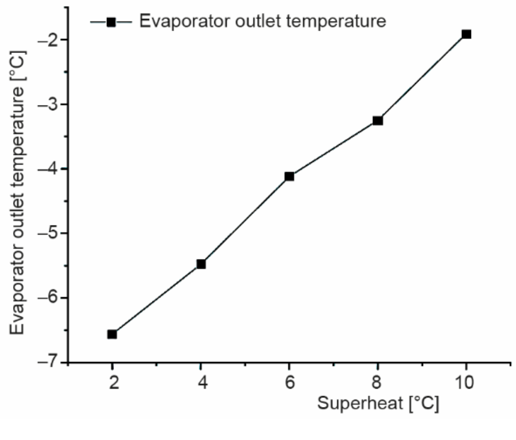

Figure 4. Variation curve of working medium temperature at evaporator outlet with superheat

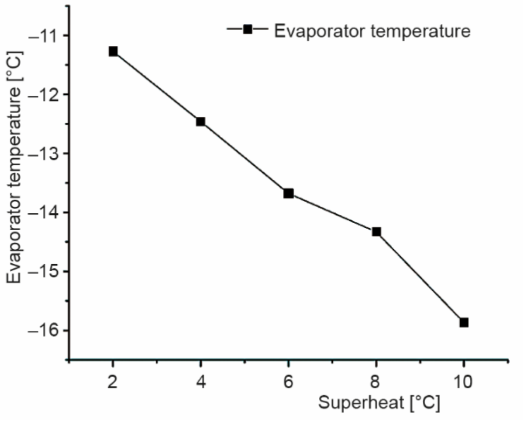

Figure 5. Variation curve of evaporation temperature with superheat

ature shows a slow downward trend. When the superheat is increased from 2 ℃ to 10 ℃, the evaporation temperature of the system decreases from –11.27 ℃ to –15.87 ℃ by 4.60 ℃. The change of the superheat of the working medium at the outlet of the evaporator seriously affects the evaporation temperature. The reason is that when the superheat at the outlet of the evaporator increases, the temperature difference collected at the inlet and outlet of the two ends of the evaporator increases and the evaporation pressure decreases. At this time, the change curve of the evaporation temperature of the system shows a downward trend.

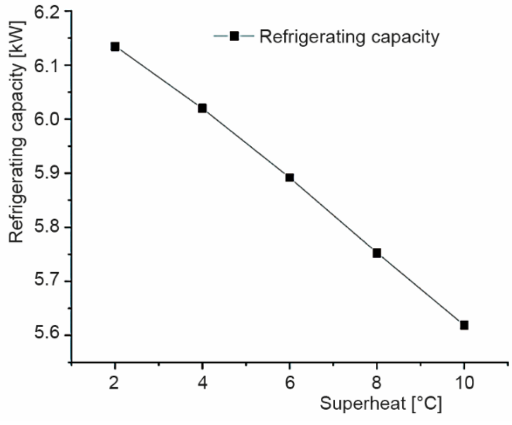

Figure 6. Variation curve of system refrigerating capacity with superheat

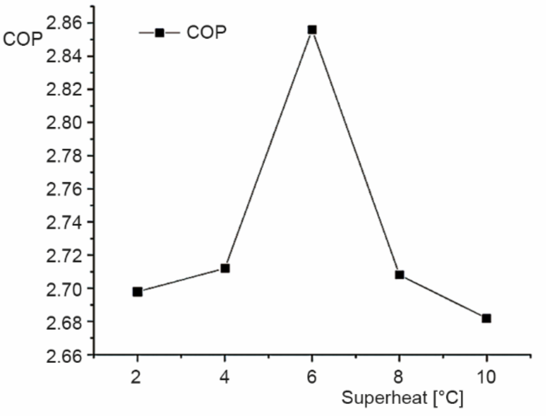

Figure 7. Variation curve of refrigeration COP of the system with superheat

Figure 6 shows the variation curve of system cooling capacity with superheat. It can be seen from fig. 6 that when the superheat of the working medium is increased, the variation curve of system evaporator cooling capacity shows a slow downward trend. When the superheat is increased from 2 ℃ to 10 ℃, the system cooling capacity decreases by 8.4%. This is because when the superheat of the working medium is increased, as can be seen from the curve change in figs. 4 and 5, the evaporation temperature shows a downward trend and the outlet temperature of the evaporator shows an upward trend, so that the specific volume of the outlet working medium of the evaporator becomes larger and the circulating quantity of the working medium of the whole system is reduced. At this time, due to the superheated gas of the outlet circulating medium, To a certain extent, the heat exchange capacity between the circulating working medium inside the evaporator and the surface air of the evaporator is attenuated, and the cooling capacity is also attenuated.

Figure 7 for COP of refrigeration system with heat curve, from fig. 7, you can see that when improve working medium degree of superheat, refrigeration COP of the system change curve showed a trend of decline after rising first and when to improve working medium heat from is 6 ℃, 2 ℃ change at this point to the naked eye can observe the change of the openness of the expansion valve is a decreasing trend, figs. 4-6 curve shows that the evaporation temperature and refrigerating capacity is on the decline, outlet temperature of the evaporator is on the rise, the condensing pressure value is smaller, but at the moment, the main factors influencing the compression ratio for the evaporating pressure decreases, so increasing the compression ratio and, in turn, the entire system is to reduce the working substance circulation, refrigerating capacity and power are reduced, the COP is the ratio of the two, However, the reduction of system power has a greater impact on COP, resulting in an increase in COP. The system COP increased from 2.698 to 2.856, an increase of 5.9%, and the maximum COP reached 2.856. Increased when the evaporator export through the heat from 6 ℃ to 10 ℃, the naked eye can observe the change of the openness of the expansion valve is a decreasing trend, the figs. 4-6 curve shows that the refrigerating capacity is on the decline, the evaporation temperature and outlet temperature of the evaporator is on the rise, the condensing pressure value is small, but at this time the main factors influencing the compression ratio for the evaporating pressure decreases, Therefore, as the compression ratio becomes larger, the circulating quantity of the whole system working medium is reduced, and the cooling capacity and power of the system are reduced. However, the reduction of the cooling capacity has a greater impact on the COP, resulting in the reduction of COP. The system COP was reduced from 2.856 to 2.682 by 6.1%. Therefore, when the outlet superheat of evaporator is 6 ℃, the system COP reaches the best value.

Conclusions

In this paper, a new electronic expansion valve is adopted. Based on the structural characteristics of the refrigerated truck refrigeration system and the characteristics of circulating working medium R404A, this experiment is designed to study and analyze the performance changes of refrigerated system under different working medium superheat. The main conclusions are as follows.

- When the superheat of the working medium is increased, the change curve of the working medium temperature at the outlet of the evaporator shows a slow increasing trend, while the change curve of the evaporation temperature and the cooling capacity shows a slow decreasing trend, and the cooling capacity decreases by 8.4%.
- When the superheat of the working medium was increased, the change curve of the system cooling COP increased first and then decreased. At this time, the optimal superheat of the working medium was 6 ℃, and the system COP was the best.
- The uniformity of temperature distribution in the evaporator can be improved by controlling the outlet superheat of the evaporator, so as to further improve the heat transfer capacity of the evaporator and improve the refrigeration performance of the system, which has certain guiding significance for the subsequent product development of the research group.

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