Application and analysis of carbon dioxide refrigeration system with ejector in commercial super cold cabinet

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Abstract. In this paper, the transcritical CO₂ refrigeration system with ejector is applied to a commercial ultra-cold cabinet. The influence of the key operating parameters of the ejector on the system performance is analyzed, and the measurement method of the experimental parameters is proposed. The results show that the ejector can eject the low pressure refrigerant into the reservoir by using the energy of the large pressure difference throttle, and the COP of the system can be increased by 9%-19%. This paper provides a theoretical basis for the design, development and optimization of CO₂ refrigeration and air conditioning system with ejector.

1 Introduction

As a natural working medium, CO₂ has the characteristics of large volume cooling capacity, high pressure, low critical point and high triple point, and has been gradually paid attention to in the supermarket refrigeration system. The performance of CO₂ system is better in subcritical operation. However, after entering the transcritical operation, the high pressure of the system increases, which will lead to the increase of compressor power consumption, the increase of irreversible loss in the process of throttling, and the great attenuation of system performance. The application of ejector in CO₂ refrigeration and air conditioning system can use the kinetic energy of ejector fluid to increase the pressure of ejector fluid, which can reduce the load of compressor and thus improve the energy efficiency ratio of the system. Many scholars have carried out abundant theoretical exploration and experimental research on CO₂ ejector refrigeration system. The experimental results show that the injector can reduce the irreversible loss in the throttling process, reduce the compressor power consumption, and improve the Coefficient of Performance (COP). Although there have been a lot of studies on CO₂ refrigeration and air conditioning system and CO₂ ejector, the CO₂ refrigeration system with ejector has not been applied in commercial super refrigerators. In this paper, the transcritical CO₂ refrigeration system with ejector is applied to a commercial ultra-cold cabinet. The influence of the key operating parameters of the ejector on the system performance is analyzed, and the measurement method of the experimental parameters is proposed. This paper provides a theoretical basis for the design, development and optimization of CO₂ refrigeration and air conditioning system with ejector.

2 Carbon dioxide refrigeration cycle with ejector

The air inlet of the injector is high pressure CO₂ gas, which changes into gas-liquid two phases in the throttle and depressurization in the injector and enters the liquid reservoir. The suction port of the ejector is connected to the evaporator outlet, and the low pressure refrigerant gas is ejected into the liquid reservoir by using the potential energy and kinetic energy when the high pressure refrigerant is throttled. The purpose is to reduce the mass flow of refrigerant into the compressor and improve the suction pressure of the compressor.

1- Compressor, 2- Gas cooler, 3- Injector, 4- Reservoir, 5- Throttle valve, 6- Evaporator, 7- Check valve, 8- Bypass valve
Figure 1. CO₂ refrigeration system with ejector

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Figure 1 shows the CO₂ refrigeration system with ejector. During summer operation, the injector is opened and the bypass valve is fully open to make the suction pressure of the compressor as close as possible to the reservoir pressure. The outlet pressure of the check valve is greater than the inlet pressure, and all the refrigerant gas from the evaporator enters the injector. It is then ejected into the reservoir. When running in winter, the driving force of the ejector drops, and the refrigerant gas from the evaporator outlet can not be ejected to the liquid reservoir. By adjusting the bypass valve and the expansion valve can make the inlet and outlet pressure of the check valve the same, the refrigerant gas at the evaporator outlet returns to the compressor through the check valve.

3 Key parameters of the ejector

3.1 Ejector ratio

The ejection ratio refers to the ratio of the mass flow of the refrigerant at the low-pressure intake port of the ejector to the mass flow of the refrigerant at the high-pressure intake port. After the design of the ejector is finalized, the ejector ratio will also be affected by the refrigerant density and compression ratio of the system.

With the increase of the optimal high pressure at the inlet, the driving force increases, the power capacity of the ejector becomes larger, and the ejection ratio increases rapidly. When the optimal high pressure of the system reaches a fixed point, if it continues to rise, the mass flow of refrigerant in the system will increase and the ejection ratio will decrease with the increase of refrigerant dryness in the liquid reservoir and the constant load of the evaporator.

3.2 The efficiency of the injector

The efficiency of the injector is the ratio of the compression work required by the isentropic expansion of the refrigerant gas entering the intake port to the reservoir pressure to the expansion work required by the isentropic expansion of the refrigerant gas entering the intake port to the reservoir pressure. When the injector efficiency is higher, the irreversible loss of the throttling process will be smaller. The factors that affect the efficiency of the ejector include nozzle design, ejector ratio optimization and lifting pressure. However, from the system point of view, the effect of injector efficiency on COP of the system is limited.

4 Experimental system and parameters measurement

4.1 The experimental system

4.1.1 The experimental device

The environment chamber is equipped with refrigeration unit, electric heater, humidifier and corresponding control and parameter testing system. The dry bulb temperature control range is -20~70 °C, and the control accuracy is ± 0.5 °C. The control range of relative humidity is 30%~98%, and the control accuracy is $\pm 1\%$, which meets the requirements of the test. In addition, according to the industry standard SB/T10794.3-2012 and the specifications of refrigerators on the market, the stereo glass single-door refrigerator is selected, with a volume of 500 L. The range and precision of the measured parameters in the experiment are shown in Table 1.

Table 1. Test ranges and accuracies of measured data

Measured parameters	Measuring instrument	Measuring range	Accuracy
Temperature	PT100	20-350°C	$\pm 0.2^\circ\text{C}$
Pressure	Pressure transducer	0-20MPa	$\pm 0.5\%$
CO ₂ flow rate	Ultrasonic flowmeter	0-600kg/h	$\pm 0.15\%$
Compressor power consumption	Digital power meter	0-20kW	$\pm 0.5\%$

4.1.2 The experimental method

First of all, the environmental chamber unit and the corresponding temperature and humidity control system should be opened to make it reach the working condition set by the test. When the environment is stable within the range of $\pm 1.1^\circ\text{C}$, 3°C and 7°C are set as the upper and lower limits of temperature by the temperature controller to realize the start-up and shutdown of the CO₂ unit. At the same time, the data acquisition instrument is used to observe the load temperature in the cabinet online. When the load temperature is stable within the temperature range

required by the test, the test is ended.

4.2 Measurement of parameters

4.2.1 Measurement of energy consumption of commercial refrigeration system

The energy consumption of the system is mainly affected by the working environment and the interior design parameters of the supermarket. The energy consumption test is mainly the acquisition and measurement of the electric parameters such as power consumption and operating current of the refrigeration system. The real-

time electric power and total electric energy consumption of each electric part of the refrigeration system, such as compressor, condenser and cabinet fan, are measured separately. Data were collected continuously for more than 24h. According to the operating power of each part and the parameters such as flow rate and pressure, the operating condition and state of the system are comprehensively analyzed. By specifying the power supply and distribution of each individual device, the measurement sequence of each part is arranged.

4.2.2 Measurement of refrigerant flow

The calculation of refrigeration capacity is an important part of refrigeration system evaluation. One of the most critical problems is the detection of traffic. Because the original system cannot be disconnected to install the flowmeter, the external equipment such as ultrasonic flowmeter can only be used for measurement. Considering the characteristics of the equipment itself and the actual situation of the site, the flow collection can only get accurate results in a specific location. If measurements must be made in a full pipe section, diameter changes and pipe bends should be avoided.

4.2.3 Measurement of integrated efficiency of refrigeration system

After the completion of a refrigeration system test, the test data should be analyzed and processed in time to calculate the COP of the refrigeration system. Then the comprehensive evaluation of the whole refrigeration system is given by considering the external environment, the influence of customer activities, the replenishment time, the cooling load of the goods and other factors.

4.2.4 Temperature data processing

Temperature data is calculated in unit of each group of refrigerators, as if a group of refrigerators is supplied by different compressor units or two liquid supply pipelines.

Average temperature. The arithmetic mean of the temperature at each point at the same time.

$$t_c(\tau) = \frac{\sum_{i=1}^N t(i, \tau)}{n} \quad (1)$$

Where: τ is the moment. n is the total number of temperature measuring points deployed.

Operating temperature. The arithmetic mean of the mean temperature at different times.

$$t_{cm}(\tau) = \frac{\sum_{i=1}^N t_c(\tau)}{N} \quad (2)$$

Where: τ is the moment. N is the total number of measurements conducted at a certain time interval and sequence within the test time.

Average temperature fluctuation value.

$$\Delta t_{c1} = t_{c\max} - t_{cm} \quad (3)$$

$$\Delta t_{c2} = t_{cm} - t_{c\min} \quad (4)$$

Where: $t_{c\max}$ is the maximum average temperature, °C. $t_{c\min}$ is the minimum of the average temperature, °C.

Temperature difference. The maximum temperature difference at different measuring points $t_c(i)$ at the same time.

$$\Delta t_c(\tau) = \{t_c(i, \tau)\}_{\max} - \{t_c(i, \tau)\}_{\min} \quad (5)$$

Temperature heterogeneity. The maximum temperature difference $t_c(\tau)$ at different times.

$$\Delta t_{c\max} = \{\Delta t_c(\tau)\}_{\max} \quad (6)$$

Average temperature difference. The difference between the highest and lowest values of the total mean temperature at each measuring point (i measuring points).

$$\Delta t_m = \left\{ \frac{\sum_{\tau=1}^N t(i, \tau)}{N} \right\}_{\max} - \left\{ \frac{\sum_{\tau=1}^N t(i, \tau)}{N} \right\}_{\min} \quad (7)$$

Where: $t(i, \tau)$ is the temperature, °C. τ is the moment. i is the temperature measuring point arranged. N is the total number of times measured in a certain time interval and sequence within the test time.

Among them, the fluctuation of working temperature and average temperature are the necessary calculation parameters, and the other parameters can be calculated according to the situation. In the actual test, due to the existence of defrosting, the above part of the parameter calculation cycle needs to select the defrosting interval stable operation stage.

5 Analysis and Conclusion

In the transcritical CO₂ system, the methods to improve COP include high-pressure pressure optimization, regenerator, two-stage compression and ejector, etc. The ejector can eject the low-pressure refrigerant into the reservoir by using the energy of the large pressure difference throttle, which can reduce the compressor power consumption and improve the COP of the system. Compared with the subcritical CO₂ refrigeration system, the COP of the ejector system increases by 9%~15% when the optimal high pressure is less than the critical pressure of CO₂. When the optimal high pressure of the system is greater than the critical pressure of CO₂, the COP of the

system increases by 10%~19% before and after the ejector is opened with the increase of the pressure.

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References

1. Wang Qi , Li Guangpeng. (2020) Research and Development of Carbon Dioxide Refrigeration Technology. E3S Web of Conferences, 213:03031.
2. MANJUNATH K, SHARMA O P, TYAGI S K, et al. (2018) Thermodynamic analysis of a supercritical/transcritical CO₂ based waste heat recovery cycle for shipboard power and cooling applications. Energy Conversion and Management, 155: 262-275.
3. J. Deng, P. Jiang, T. Lu, W. Lu. (2007) Particular characteristics of transcritical CO₂ refrigeration cycle with an ejector, Appl. Therm. Eng. 27:381-388.
4. F. Liu, Y. Li, E.A. Groll. (2012) Performance enhancement of CO₂ air conditioner with a controllable ejector, Int. J. Refrigeration 35:1604-1616.
5. Hafner A, Frsterling S, Banasiak K.(2014) Multi-ejector concept for R -744 supermarket refrigeration. International Journal of Refrigeration, 43(4) : 1-13.