Experiments on an Open-Loop Cycle Carbon Dioxide Refrigeration System

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Abstract: An open loop cycle carbon dioxide (CO_2) refrigeration system is established, and the cooling performances of high-pressure CO_2 under different storage conditions (25℃, 30℃, and 35℃) are investigated. Moreover, the experimental mass flow rates of CO_2 are compared with the theoretical values at different conditions and refrigeration capacities. The results indicate that the storage condition of CO_2 has a significant impact on the refrigeration performance, and the mass flow rate of CO_2 increases with the increasing storage temperature in a given refrigeration capacity.

Key words: CO_2; open loop cycle refrigeration system; mass flow rate; storage condition

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0 Introduction

Nowadays, ozonosphere depletion and the greenhouse effect become serious problems. To reduce these effects, natural refrigerants are promising replacements for chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants. Carbon dioxide (CO_2) is an ideal natural refrigerant thanks to its characteristics, such as safety, non-toxicity, renewability, and environment friendliness[1]. In addition, its wide variety of sources and low prices make CO_2 a good choice for small enclosed spaces like refuge chambers and evacuation chambers. In general, the refrigeration systems for small enclosed spaces can be classified as ice storage refrigeration, electrical storage refrigeration, and high-compressive gas refrigeration. Although ice storage refrigeration is safe, simple, and easy to implement, the system needs auxiliary equipment for ice reservation during normal times, thus leading to high maintenance costs and high energy mass flow rates. In electrical storage refrigeration, it is easy to control temperature and humidity effectively, and the system is mature with low failure rates and low maintenance costs[2]. However, the manufacturing costs of explosion-proof batteries are high, and the refrigeration performance is influenced by the external environment[3].

Traditional closed-loop cycle CO_2 refrigeration systems need active power compressors for operation[4-5]. A comparative study of open-cycle and closed-cycle absorption cooling demonstrates that the former has better performance, is less expensive, and uses simpler technology[6]. Moreover, in light of recent coal-mine disasters, the no-power open-loop cycle CO_2 refrigeration could improve equipment reliability. The low cost, high independence, high operating pressure of CO_2—which can even be used to drive the pneumatic fan—and the low maintenance costs of CO_2 storage become the advantages of CO_2 refrigeration[7]. To ensure the reliability of the open-loop cycle CO_2 refrigeration system and avoid the formation of dry ice, the flow resistance of the long evaporation coils is increased so that the pressure increases after throttling. Furthermore, the refrigeration performance of high-pressure CO_2 un-

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der three different storage conditions are investigated, and the influencing factors of the open-loop cycle CO_2 refrigeration system are considered theoretically and experimentally[8].

Cao[9] and Yang[10] studied the refrigeration system performance of the open-loop cycle CO_2 under different storage conditions. There is a large cooling-capacity loss under the supercritical condition. They addressed the factors influencing the performance in the single throttling system, without any optimization of the design[11]. A two-stage throttling system without frost has been studied recently, which can raise throttling temperature up to 0 ℃, and the system is highly adaptable to different temperature and humidity with a shorter length of the evaporator.

1 Theoretical Analysis of Influence of Different Storage Conditions

For the purpose of comparing the cooling performances of subcritical, closed critical, and supercritical open-loop CO_2 refrigeration systems, the critical temperature of CO_2 (31.1 ℃) is considered. Since the CO_2 cylinders are placed in the equipment compartment, the CO_2 storage temperature becomes the same as the equipment temperature when reaching the heat balance. The equipment compartment temperature is controlled at 25, 30, 35 ℃ under the different experimental conditions. After testing the experimental equipment and the measuring instrument, the system is switched on. The following parameters are determined, i.e., temperature and pressure at the outlet of the high-pressure cylinder, the inlet and outlet of the primary evaporator, and the exhaust outlet. In Fig. 1, the cooling process 1—2—3—4 represents the ideal open subcritical loop cycle refrigeration system for 25 ℃ storage temperature, whereas the process 1′—2′—3′—4′ represents the ideal open critical system close to the critical point for 30 ℃ storage temperature. Another process 1″—2″—3″—4″ represents the ideal open supercritical loop cycle refrigeration system for 35 ℃ storage temperature.

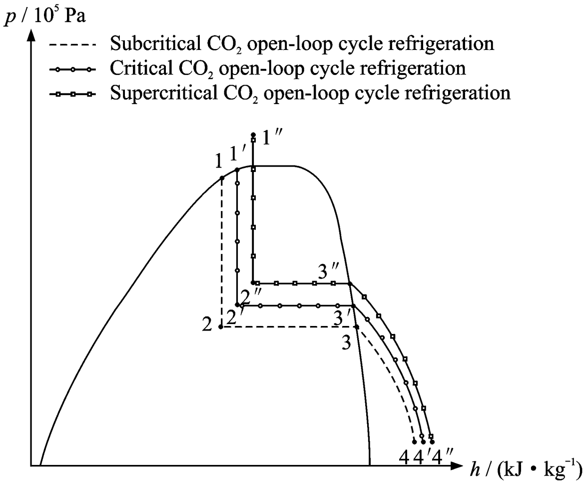

Fig. 1 Pressure-enthalpy (p-h) diagrams for open-loop cycle CO_2 refrigeration processes

To meet the design requirements of the coal-mine escape capsule, the temperatures of the closed spaces are not over 35 ℃, which is the critical temperature of the crew compartment. Therefore, the effective operating time period is between the beginning of the experiment and the time when the crew compartment temperature reaches 35 ℃. For the experiments under the three typical storage conditions, the mass of CO_2 (M) is known for the effective operating time t. The experimental mass flow rate q_e is then given by Eq. (1).

$$q_e = M/t \tag{1}$$

The pressure-enthalpy (p-h) graph of the CO_2 refrigeration system can be used to calculate the theoretical mass flow rate q_t of the CO_2 cooling process for the experimental crew compartment.

$$q_t = (Q_t - Q_l)/(h_0 - h_t) \tag{2}$$

where Q_t, Q_l, h_0, h_t are the total heat load (2 400 W) of the crew compartment, leakage heat loss of the crew compartment at the storage condition time, initial enthalpy of CO_2, and theoretical discharge enthalpy of CO_2.

The CO_2 in the cylinders is in a gas-liquid mixed state, where the gas and liquid are both saturated. At different temperatures and pressures, CO_2 has different gas-liquid ratios as listed in Table 1. The volume of the CO_2 cylinder is 40 L, and the net weight of CO_2 is 18 kg.

Table 1 Gas-liquid ratios of CO_2

Storage temperature/℃	Saturated liquid		Saturated gas		Dryness
	Volume/m^3	Mass/kg	Volume/m^3	Mass/kg	
25	17.75	12.64	22.25	5.36	0.28
30	17.45	10.33	22.55	7.67	0.43
35	—	—	40	18	—

The processes 1—2, 1′—2′, and 1″—2″ represent the throttling of CO_2 in the pressure-reducing valve. During the processes, CO_2 changes from saturated liquid (25 ℃ and 30 ℃) or supercritical gas (35 ℃) to the gas-liquid mixed state and the temperature and pressure of CO_2 are reduced. The processes 2—3, 2′—3′, and 2″—3″ represent the evaporation of CO_2, during which it changes from liquid to gas, at constant temperature and pressure. The processes 3—4, 3′—4′, and 3″—4″ represents the heat transfer processes, where CO_2 is evaporated completely, the pressure of CO_2 in the evaporator coils is reduced, and the pressure energy is converted to internal energy, thus releasing cold energy.

2 Materials and Method

2.1 Experimental system

Fig. 2 shows the experimental system of the open-loop cycle CO_2 air-conditioning for small enclosed spaces, including an experimental cabin, main refrigeration equipment, and measuring instruments. The experimental cabin comprises the equipment compartment and crew compartment. The equipment compartment holds the CO_2 high-pressure cylinder, and an electric heater is controlled with a solenoid valve to simulate the ambient temperature for the three storage conditions. In order to imitate the structural thermal load and human thermal load on the capsule, the load supply equipment (sufficient bulbs) is installed in the crew compartment. The main refrigeration equipment consists of a CO_2 compressed cylinder, a pressure-reducing valve, evaporator coils, and a fan for the cooling system[12]. The industrial liquid CO_2, from the Nanjing Special Gas Limited Company, has 99.8% purity, and the filling coefficient of the standard 40 L CO_2 cylinder is 0.6. The CO_2 cylinder is placed in the experimental environment more than 2 h before the CO_2 experiment to ensure that the temperature satisfies the test requirements. The pressure-reducing valve is of the *R*12 diaphragm-type from the Hangzhou Baoyan Instrument Limited Company. The evaporators use ∅6 mm (wall thickness is 1 mm) red coppers for three evaporator coils (the diameter of each coil is 1 m), connected as shown in Fig. 2. The total length of the evaporator coils is 300 m.

The CO_2 refrigerant is a consumable substance, discharged from the equipment compartment evaporator coils during the working process. Therefore, it is essential to calculate the CO_2 refrigerant consumption for the refrigeration design of refuge spaces to meet designed hedging using time. For example, the KJYF-96/12 coal-mine mobile escape capsule needs 46 CO_2 cylinders (70 L) to keep the crew compartment temperature below 35 ℃ and relative humidity under 85%. The measuring instruments include platinum resistances and pressure transmitters for measuring the ambient temperature and pressure of the equipment compartment, outlet temperature and pressure of the CO_2 compressed gas cylinder, outlet temperature and pressure of the pressure-reducing valve, outlet temperature and pressure of the primary and secondary evaporator coils, as well as external temperature and pressure. The test measuring instruments are listed in Table 2.

The platinum resistance has an accuracy of Grade B, according to the machinery industry standard JB/T 8622. Therefore, the maximum error is the industry maximum error of Grade B: $\pm(0.3+0.005|t|)$ ℃, where $|t|$ is the absolute temperature. The maximum temperature of the experiment does not exceed 50 ℃, so the maximum error is: 0.3+0.005×50=0.55 ℃, which is 0.55/200=0.275% of the full range. The accuracy of the pressure transmitter is 0.75%, the maximum range 10 MPa, and the error 0.75×10/100=0.075 MPa. Moreover, the output signal range is 4—20 mA, the transmission accuracy of the current signal 0.01 mA, and the signal conversion error 0.01×10/16=0.006 25 MPa. Therefore, the total error is 0.075+0.006 25=0.081 25 MPa, which is 0.812 5% of the full range.

The temperature and pressure of CO_2 released from the high-pressure cylinder are reduced by the pressure-reducing valve, and then the CO_2 flows through the primary and secondary evaporator coils, where the liquid CO_2 becomes gaseous and absorbs the heat in the crew compartment[13]. Therefore, the open-loop cycle refrigeration system can effectively control the temperature of small enclosed spaces to ensure human health and safety[14].

2.2 Experimental procedure

The experimental procedure is:

(1) The test monitoring system is switched on, and the operation of the platinum resistances and pressure transmitters is checked.

(2) The temperature control equipment of the equipment compartment is switched on, and the equipment compartment temperature (CO_2 storage temperature) is controlled at 25, 30, and 35 ℃.

(3) The air-circulating fan in the crew compartment is switched on.

(4) The pressure-reducing valve of the cooling system is switched on, and the pressure after the valve is regulated to 3.5 MPa.

(5) The changes in the temperature and pressure of the cooling system are recorded, and the cooling system is switched off when the crew compartment temperature reaches 35 ℃.

2.3 Uncertainty analysis

From the measured data, the relevant parameters are acquired using the CO_2 pressure-enthalpy diagram. The high-precision pressure transmitter and the thin disk high-precision platinum resistance are used in this experiment. The

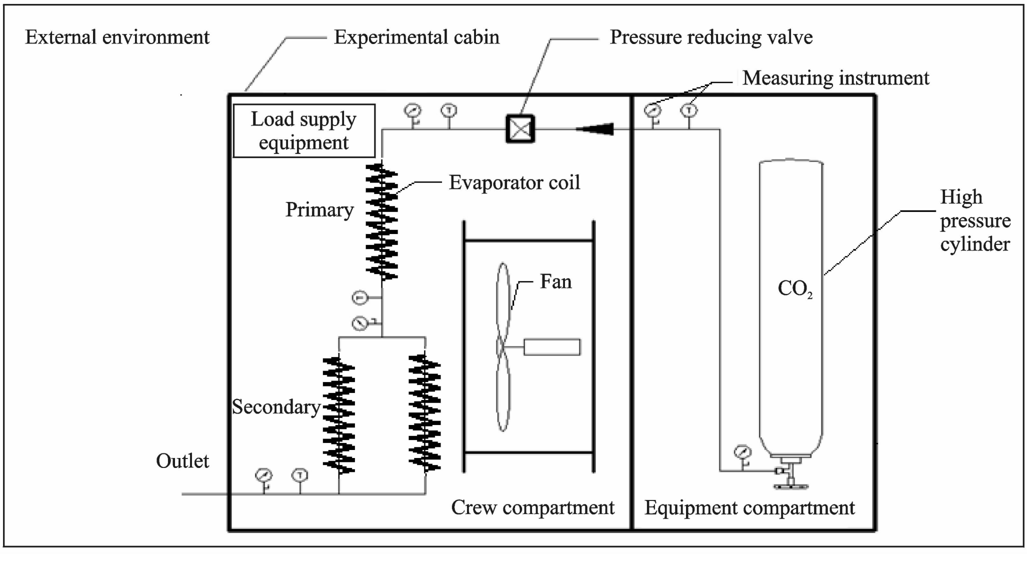

Fig. 2 Open-loop cycle CO_2 refrigeration experimental system

Table 2 Test measuring instruments

Name	Type	Number	Measuring range	Company	Accuracy
Platinum resistance	Pt100	4	−50—150 ℃	Njlerun Ltd.	Grade B
Pressure transmitter	M5156-000002-100BG	1	0—10 MPa	Measurement Specialties Inc.	±0.75%
Pressure transmitter	M5156-000002-050BG	1	0—5 MPa	Measurement Specialties Inc.	±0.75%
Pressure transmitter	M5156-000002-030BG	1	0—3 MPa	Measurement Specialties Inc.	±0.75%
Pressure transmitter	M5156-000002-016BG	1	0—1.6 MPa	Measurement Specialties Inc.	±0.75%

platinum resistance is fixed on the outside surface of the evaporator coils using thermal conductive silicone to improve the measurement accuracy.

The initial temperature of CO_2 in the experiment is an important factor in the calculations. Therefore, in order to ensure its measurement accuracy, the CO_2 cylinders have to be preserved at the experimental temperature (25, 30, 35 ℃) for more than 2 h, with full heat transfer between the CO_2 and the equipment compartment so that the refrigerant temperature approximates the equipment compartment temperature. However, the external environment causes small-range fluctuations, changing the heat load and crew compartment temperature.

From the accuracy and error calculations for the aforementioned test instruments, the uncertainties of the platinum resistance and pressure transmitter are 0.275% and 0.812 5%, respectively[15]. In summary, although small-range deviations exist between the experimental results and theoretical calculations of the cooling performance of the open-loop cycle CO_2 refrigeration, the results provide theoretical evidence for its engineering application. The detailed calculations and analysis of the experiment are not presented here.

2.3 Experiment for leakage heat loss of crew compartment

Due to the temperature difference between the crew compartment and the external environment, the heat leakage loss of the crew compartment has to be considered for accurately estimating thermal load. The heat load was simulated at 600, 1 000, 1 200 W, and the temperature of the crew compartment was measured until the external environment and the crew compartment reached an equilibrium.

Considering the last 5 min of the experimental temperature difference between the crew compartment and the external environment, the product of heat transfer coefficient K and heat transfer area A is obtained according to the equation of heat balance.

$$KA = Q_s/(T_{bc} - T_{ba}) \tag{3}$$

where Q_s, T_{bc}, and T_{ba} are the simulated heat load, equilibrium crew compartment temperature, and equilibrium ambient temperature, respectively.

Then, the leakage heat loss of the crew compartment is

$$Q_l = \overline{KA}(T_c - T_a) \tag{4}$$

where T_c and T_a are the crew compartment temperature and the ambient temperature, respectively.

Eqs. (2), (4) can be combined to obtain the following formula

$$q_t = [Q_t - \overline{KA}(T_c - T_a)]/(h_0 - h_t) \tag{5}$$

3 Results

3.1 Analysis of factors influencing cooling performance

3.1.1 Effects on cooling performance under different storage conditions

For the storage temperature of 35 ℃, the temperature and pressure at the key measuring points are shown in Figs. 3,4, respectively. It can be seen that from 0 min to 5 min, by adjusting the pressure-reducing valve, the outlet pressure of pressure-reducing valve decreases, and the gas supply temperature and outlet temperatures of the primary evaporator coils and pressure-reducing valve also decrease. From 5 min to 24 min, the gas supply pressure decreases, whereas the outlet pressure of the pressure-reducing valve remains stable. Therefore, their pressure difference decreases. In addition, since the throttling effect weakens during this period, the outlet temperature of the pressure-reducing valve and inlet temperature of the primary evaporator coils increase. From 24 min to 35 min, the reduction in the gas supply pressure is less than that in the outlet pressure of the pressure-reducing valve, so their pressure difference increases. Moreover, the throttling effect is enhanced during this period, so the inlet and outlet temperatures of the primary evaporator and outlet temperature of the pressure-reducing valve decrease. From 35 min to

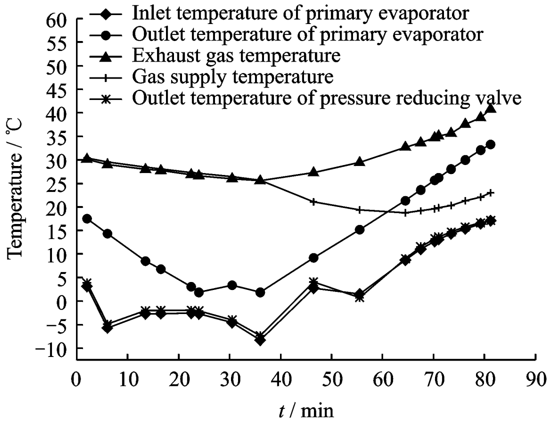

Fig. 3 Temperature variation with time for the refrigeration system

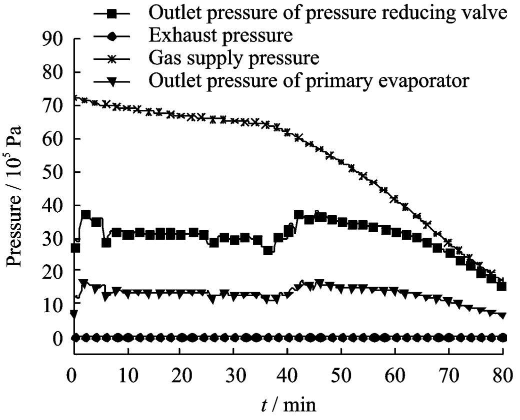

Fig. 4 Pressure variation with time for the refrigeration system

47 min, the difference between the gas supply pressure and the outlet pressure of the pressure-reducing valve decreases continually, whereas the inlet and outlet temperatures of the primary evaporator and outlet temperature of the pressure-reducing valve gradually increase. After 47 min, owing to limited CO_2 and insufficient cooling capacity, the inlet and outlet temperatures of the primary evaporator and outlet temperature of the pressure-reducing valve sharply increase as a result of the increased heat transfer from the crew compartment environment to the evaporator coils. Meanwhile, thanks to the sustained heating of the electric heater controlled by the solenoid valve, the inlet gas temperature of the entire CO_2 refrigeration system is maintained at about 30 ℃. Eventually, the exhaust gas temperature becomes larger than the gas supply temperature. This demonstrates that the parameters of the supercritical refrigeration system are non-steady, and therefore the refrigeration capacity loss must be larger than in the critical and subcritical refrigeration systems.

3.1.2 Comparison of experimental and theoretical mass flow rates of CO_2

Fig. 5 shows the average temperature of the equipment compartment during the 1 h experimental process. The refrigeration capacity of CO_2 under a certain condition is limited by the temperature of the equipment compartment. Considering of the unstable flow of CO_2, there is a significant fluctuation in the average temperature of the equipment compartment. When the cooling capacity is less than the heating capacity, the crew compartment temperature rises and vice versa. In the end, when the liquid CO_2 in the cylinder is used up, the cooling effect weakens, and the crew compartment temperature thus gradually increases. For the experiment, the crew compartment temperature of 35 ℃ was taken as the standard to judge the cooling performance of the open-loop cycle CO_2 refrigeration system at the three different storage temperatures.

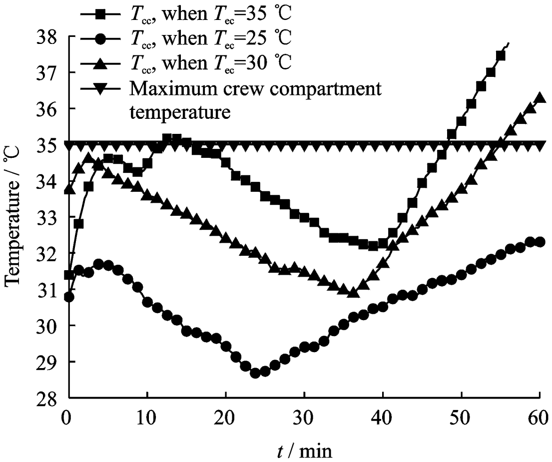

Fig. 5 Average temperature variation of crew compartment with time at different temperatures of equipment compartment

Table 3 shows the effect of the equipment compartment temperature on the mass flow rate of CO_2. It can be seen that the mass flow rate of the CO_2 refrigerant increases as the equipment compartment temperature increases. According to the pressure-enthalpy diagram of CO_2, the initial enthalpy and theoretical discharge enthalpy are influenced by temperature and pressure. It is assumed that the theoretical discharge temperature and theoretical discharge pressure are close to the average ambient temperature and barometric pressure (1.01 bar). The experimental and theoretical mass flow rates of CO_2 can then be calculated using Eqs. (1), (5), respectively. The mass flow rate of CO_2 at the equipment compartment temperature of 35 ℃ is much larger than that at 25 ℃ or 30 ℃, confirming the loss of refrigeration capacity at supercritical throttling. Hence, to decrease the loss of refrigeration capacity and increase the operating rate, the storage temperature of CO_2 in the equipment compartment should be controlled below 31.1 ℃. As the high-pressure CO_2 cylinders are located in the equipment compartment, the storage temperature will become the same as the equipment compartment temperature after a long period of operation. Moreover, the heat transfer of liquid CO_2 mainly occurs in the crew compartment rather than in the equipment compartment. Therefore, the theoretical discharge temperature is irrelevant to the storage temperature and influences only the crew compartment temperature. Since the equipment compartment has no heat load and the CO_2 evaporation process absorbs heat from the equipment compartment environment, the storage temperature is lower than the crew compartment temperature. Therefore, the theoretical discharge temperature is higher than the storage temperature.

All the theoretical data are obtained from the pressure-enthalpy diagram and the performance parameters of CO_2. It is assumed that the theoretical discharge temperature and theoretical discharge pressure are close to the average ambient temperature and barometric pressure (1.01 bar). Using the pressure-enthalpy diagram of CO_2 (model), the initial enthalpy can be obtained from the storage temperature and pressure, and the theoretical discharge enthalpy can be obtained from the theoretical discharge temperature and pressure. Then, the experimental and theoretical mass flow rates of CO_2 can be calculated by Eqs. (1, 5).

Table 3 Thermal parameters of CO_2 under different storage conditions

Storage temperature/℃	Storage pressure/ 10^5 Pa	Initial enthalpy/ $(kJ \cdot kg^{-1})$	Theoretical discharge temperature/℃	Theoretical discharge pressure/10^5 Pa	Theoretical discharge enthalpy/$(kJ \cdot kg^{-1})$
25	64.2	314.32	30	1.01	506
30	72.1	334.70	30	1.01	506
35	80.2	345.69	30	1.01	506

3.2 Leakage heat loss

From the experiment for the leakage heat loss of the crew compartment, the variations in ambient temperature and crew compartment temperature with heating time at 600 W heat quantity are shown in Fig. 6.

The difference between the balanced ambient temperature and the crew compartment temperature, and the value of *KA* are calculated based on Fig. 3 and Eq. (1). The results are shown in Table 4 for the different heat quantities, and the average value of *KA* is 49.124 W/℃.

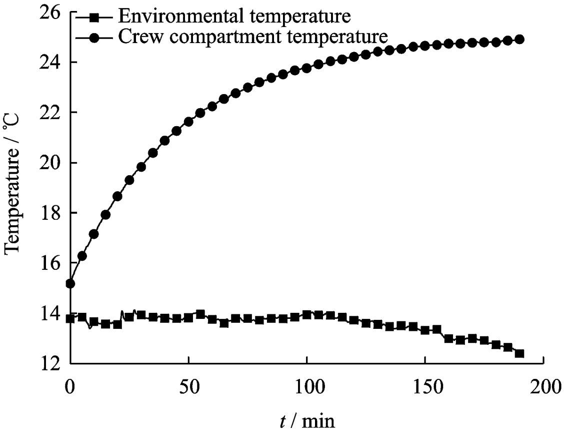

Fig. 6 Variation of ambient temperature of crew compartment with heating time at 600 W

Table 4 ***KA* for different heat quantities of crew compartment**

Heat quantity/W	Temperature difference/℃	KA/ (W · ℃$^{-1}$)
600	12.465	48.135
1 000	20.382	49.063
1 200	23.917	50.174
The average of KA		49.124

From Eq. (5), with $Q_t = 2\ 400$ W and $\overline{KA} = 49.124$ W/℃, the experimental mass flow rates of CO_2 under different storage conditions are calculated, and the values are compared with theoretical mass flow rates in Table 5.

Table 5 Comparison of experimental and theoretical mass flow rates of CO_2

Storage temperature/ ℃	Storage pressure/ 10^5 Pa	Theoretical mass flow rate of CO_2/(kg·h^{-1})	Experimental mass flow rate of CO_2/(kg·h^{-1})
25	64.2	21.41	21.60
30	72.1	23.95	27.46
35	80.2	25.60	39.27

4 Conclusions

An open-loop cycle CO_2 refrigeration system is tested for a closed space without electrical energy, and the factors influencing its performance are studied experimentally. Based on the experimental data, the theoretical and experimental mass flow rates of CO_2 are then analyzed and compared. The following conclusions can be drawn:

(1) The theoretical mass flow rate of CO_2 at the storage temperature of 25 ℃ is closest to the experimental value, indicating that lower storage temperature and larger CO_2 cooling capacity leads to longer cooling time and higher cooling performance.

(2) When the mass of CO_2 in the cylinder remains constant, there is a direct relationship between the temperature and pressure of the CO_2 in the cylinder. The results manifest that the storage conditions (storage temperature) of CO_2 have significant impact on the refrigeration performance and the mass flow rate of CO_2 becomes larger as the storage temperature increases.

These results provide a useful reference to the study of the open loop cycle CO_2 refrigeration system.

The state and distribution of refrigerant of system have been investigated recently, as well as the influence of temperature change. The design of secondary throttle system is optimized experimentally. It provides an important reference to the research and application of the open-loop cycle CO_2 refrigeration system under the extreme conditions.

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