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EXPERIMENTAL INVESTIGATION ON CO_2 EJECTOR-EXPANSION REFRIGERATION SYSTEM FOR BATTARY PACK COOLING

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ABSTRACT

In this study the performance characteristic of a CO_2 ejector-expansion system applied for battery pack cooling is investigated. An experimental bench is set up and the performance of the system is experimentally studied under different working conditions. The cooling capacity and COP of the system decrease with the increasing of gas cooler outlet temperature. There is an optimal opening degree of EEV for both the capacity and COP to get a maximum value. The entrainment ratio of the ejector is improved by introducing an IHX. Compared with the basic cycle, ejector-expansion system can improve both the cooling capacity and COP significantly, around 21.7% increment in cooling capacity and 28.0% increment in COP, respectively.

Keywords: ejector-expansion refrigeration, CO_2, battery cooling

NONMENCLATURE

Abbreviations

PLR	Pressure lift ratio
COP	Coefficient of Performance

Symbols

Cp	Specific heat capacity, J/(kg°C)
H	Enthalpy, J/kg
M	Mass flow rate, kg/s
P	Pressure, Pa
Q	Cooling capacity, W
T	Temperature, ℃
W	Work， W
M	Entrainment ratio

Subscripts

B	Basic cycle
e	Exit of the ejector
in	Inlet
out	Outlet
p	Primary fluid
s	Secondary fluid
w	Water

1. INTRODUCTION

Electrical vehicles (EVs) have become a significant developing trend of the automobile industry due to its environmental characteristics. However, the immature thermal management of the power battery groups is one of the key factors hindering the development of EVs.

As the charging and discharging process of the battery is accompanied by a large amount of reaction heat, the battery temperature gets raised sharply, severely affecting the efficiency and service life of the battery, even security risks [1]. For a Li-ion battery, 25 - 40°C is the ideal temperature for efficient and reliable operation [2]. Khateeb et al. presented that there might be safety risk when the Li-ion battery operated at the temperature above 70℃ [3]. It is significant to search for efficient cooling method for power battery. Up to now, battery cooling system is integrated to the air conditioning system, no matter using air, liquid, phase change material or heat pipes to build up the cooling system [4-5]. However, a large amount of heat will impact the air-conditioning system, and its operation stability will get worse for the integrated system, especially for the large vehicle like electric bus. Therefore, the independent battery cooling system is also a potential development direction.

The replacement of environmental refrigerant is another challenge in the field of automobile. Natural working medium CO_2 stands out from others due to its excellent environmental characteristics. However, the performance of the basic trans-critical CO_2 system is poor as the outdoor temperature is higher than 35°C, and the ejector-expansion refrigeration system, recovering the expansion losses by introducing an ejector, had been

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proposed. Many studies have been concerned with the performance of the ejector-expansion system, both in simulation and experiment. The results showed that the ejector-expansion can improve the performance of the system by 20% compared with a basic cycle [6-7].

Since the excellent performance of the ejector-expansion refrigeration system, this study employs an ejector system for spilt battery pack cooling. The cooling capacity and coefficient of performance (COP) of the ejector-expansion system were analyzed under various gas cooler outlet temperature, electrical expansion valve (EEV) opening and compressor speed. The performance of ejector-expansion system was compared with that of the basic cycle. In addition, the impact of the internal heat exchanger (IHX) was analyzed by comparing with a system without IHX.

2. EXPERIMENTAL SETUP

2.1 Experimental system

Fig. 1 shows the schematic diagram of the CO_2 ejector-expansion refrigeration system applied in power battery cooling for electric bus. The system is mainly composed of a compressor, a plate heat exchanger used as gas cooler, a dryer, a two-phase ejector, a separator, an EEV, a plate heat exchanger used as evaporator (chiller for the battery loop) and another plate heat exchanger as internal exchanger, etc. In addition, the experimental system also composites of a battery loop, including battery and pump. The dryer arranged in front of the ejector is mainly used to avoid ice blockage in the throat of the ejector. The ejector plays a role in reducing throttling losses under large pressure differences. The separator is used to separate the outflow of the ejector into liquid and vapor phase. The liquid is expanded in the EEV and then sucked into the ejector after being evaporated, while the separated vapor refrigerant enters the internal heat exchanger and then the compressor. The discharging vapor is cooled down preliminarily in the

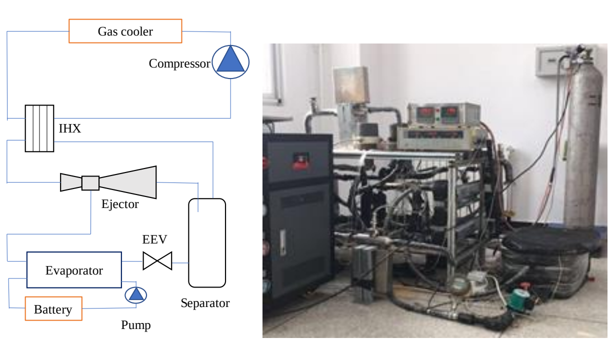


Fig 1 The CO_2 ejector-expansion system for battery cooling

gas cooler and then cooled secondly in the internal heat exchanger by the vapor form the separator.

The compressor is a 6cc scroll compressor, working in the frequency range from 45 to 120 Hz. The compressor is driven by a 2.5kW invertor which can transform the 220V alternating current (50 Hz) into direct current with pre-set frequency. The capacity for both gas cooler and evaporator is 5kW while 1.5kW for the internal heat exchanger. Fig. 2 shows the structure of the ejector used in this system.

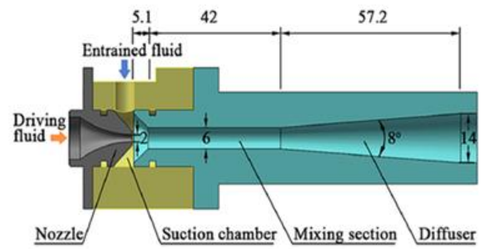


Fig 2 The structure of the ejector

The measurements used in the experiment and the accuracy are listed in Tab. 1.

Tab 1 The accuracy of measuring instruments

Measuring instruments	Uncertainties
Temperature sensors (Pt 100)	± 0.2℃
Pressure transducers	± 0.5 %
Mass flow rate	± 0.15%
Digital power meter	± 0.5%

2.2 Data reduction

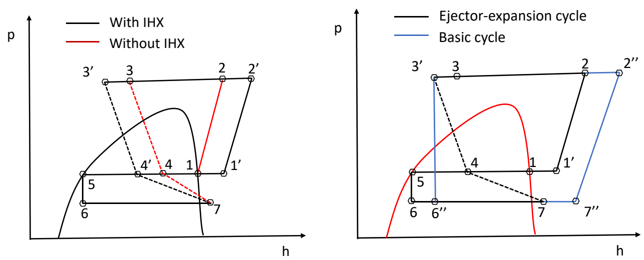
Fig. 3 is the *p-h* diagram of the CO_2 ejector-expansion system. The primary fluid (point 3) enters the nozzle of the ejector, resulting in high speed and low pressure. And then gets mixed with the secondary fluid (point 7) sucked from the evaporator. Then the mixed fluid enters the diffuser, with the speed dropping and the pressure increasing, becoming two phase fluid leaving the ejector (point 4). The dash lines 3'-4 and 7-4 in Fig. 3 dedicate the processes occurring in the ejector virtually.

The entrainment ratio μ and the pressure lift ratio PLR are always used to evaluate the performance of the ejector. The entrainment ratio, defined as the ratio of the mass of secondary fluid to the primary fluid, characterizes the drainage capability of the ejector.

$$\mu = \frac{m_s}{m_p} \qquad \text{Eq. (1)}$$

The secondary fluid, exiting from the evaporator, gets mixed with the primary fluid and then the pressure increases in the diffuser. The pressure of the ejector outlet fluid equals to the compressor suction pressure. The work is reduced as the suction pressure is higher than the evaporative pressure. The pressure lift ratio, defined as the ratio of the ejector outlet pressure to the pressure of the secondary fluid.

$$PLR = \frac{P_e - P_s}{P_P - P_s} \qquad \text{Eq. (2)}$$



(a) (b)

Fig 3 The p-h diagram of the CO_2 ejector-expansion system

Fig. 3(a) shows the comparison of the ejector cycle with an IHX or not. In the IHX, the outlet flow of the gas cooler is cooled down by the suction vapor. The main difference of the system with an IHX performs in the suction super-heat, discharge temperature and temperature of the primary fluid.

The capacity can be calculated from the temperature difference between the inlet and outlet water in chiller:

$$Q = m_w \times C_p \times (T_{w,in} - T_{w,out}) \qquad \text{Eq. (3)}$$

Then the COP is expressed as:

$$COP = \frac{Q}{W} \qquad \text{Eq. (4)}$$

Where W is measured by power meter.

For comparison, a basic cycle defined as 7′′-2′′-3′-6′′is shown in Fig. 3(b). Line 7′′-2′′, paralleled to 1′2, represents the compression process with the same compressor efficiency with the ejector cycle. Vertical line 3′-6′′ means the isenthalpic throttling process in the EEV. Line 7-7′′, the same in length with 1-1′, represents the process in the IHX with equal heat in the ejector cycle.

The capacity of the basic cycle is defined as:

$$Q_b = m_b \times (h_7 - h_{3'}) \qquad \text{Eq. (5)}$$

The work is defined as:

$$W_b = m_b \times (h_{2''} - h_{7''}) \qquad \text{Eq. (6)}$$

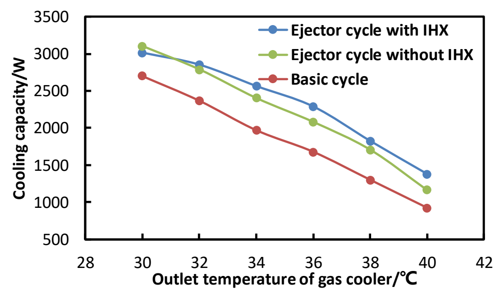
Then the COP of the basic cycle is expressed as:

$$COP_b = \frac{Q_b}{W_b} = \frac{h_7 - h_{3'}}{h_{2''} - h_{7''}} \qquad \text{Eq. (7)}$$

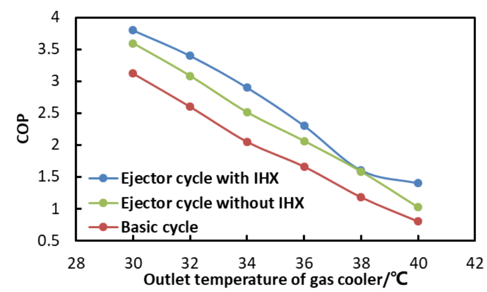
3. RESULTS AND DISCUSSION

3.1 The effect of gas cooler outlet temperature

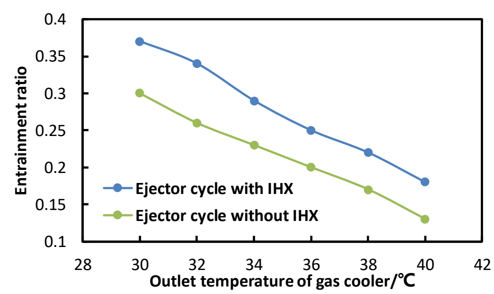
The gas cooler outlet temperature varies from 30 to 40℃ with a constant volumetric flow of 0.3m^3/h to observe the performance variations. During the test, the



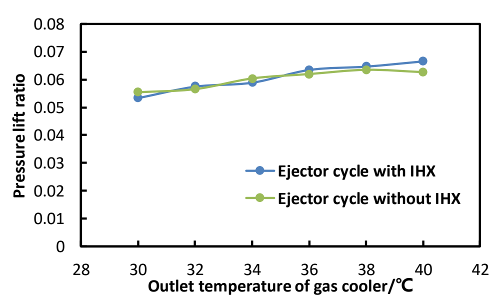
(a) Cooling capacity



(b) COP



(c) Entrainment ratio



(d) Pressure lift ratio

Fig 4 The performance of the system and the ejector for different gas cooler outlet temperature opening of the EEV is 39.3% where the system operates with an optimal performance, and the rotation speed of the compressor is 3300 rpm. Fig. 4(a) indicates that the capacity of both ejector cycle and basic cycle decrease significantly with an increase in the gas cooler outlet temperature and the cooling capacity of ejector-expansion system increased by 11.6% compared to a basic cycle. Fig. 4(b) shows the COP for different gas cooler outlet temperature. The results indicate that the COP of ejector cycle is 21.7% higher than that of the basic cycle while both of them suffering a sharply drop with the increase in the gas cooler outlet temperature

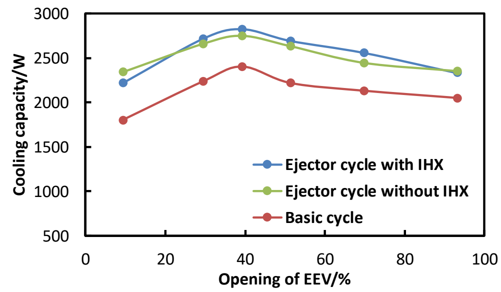
Fig.4(c) shows that the IHX plays an important role in improving the entrainment ratio of the ejector, with an increase by 23.3%. On the other hand, the pressure lift ratio suffers a little attenuation with the introducing of the IHX, resulted from the pressure drop in the IHX.

3.2 The effect of opening of EEV

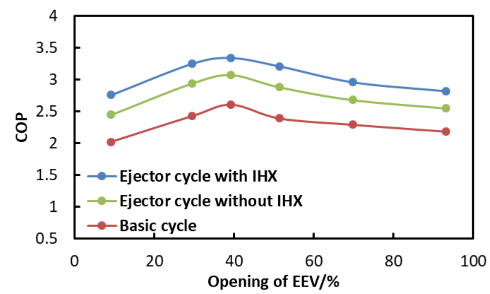
The EEV opening is an important parameter to ensure the system work in a stable condition. Tests were carried out with the EEV opening varies from 9.4% to 93.2%. Change the opening degree by adjusting the driving voltage from 0-5V since the opening degree is proportional to the driving voltage with a scale factor of 0.192. As the opening degree increases, the throttling effect decrease, the difference of pressure between the EEV inlet and outlet change from 0.35MPa to 0.13MPa while the temperature difference varies from 2.8 to 1.2. On the other hand, the mass flow of the second fluid varies from 33.42 kg/h to 44.6 kg/h as the opening increasing.

Fig. 5(a) shows the cooling capacity for different opening degree of the EEV. The result indicates that there is a maximum cooling capacity as the opening increasing. When the EEV is opened at 39.3%, the system has the maximum cooling capacity, 2824W. Fig. 5(b) shows the trend of the three systems affected by the EEV opening is similar. As the opening is 39.3%, the maximum COP the ejector-expansion system and basic cycle are 3.34 and 2.61. Both ejector cycle with and without IHX can improve system performance significantly, with 28.0% and 16.1% increment respectively.

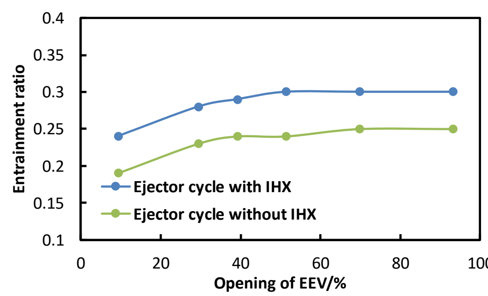
Fig.5(c) indicates that the entrainment ratio of the ejector increases with the increase in the opening of the EEV while the pressure lift ratio decreasing, largely because of the increase in the mass flow of the secondary flow. As the opening increase from 0-100%, the throttle effect of the EEV decrease. And the pressure difference between the refrigerant vapor from



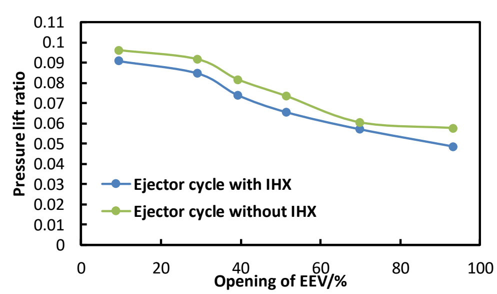
(a) Cooling capacity



(b) COP



(c) Entrainment ratio



(d) Presure lift ratio

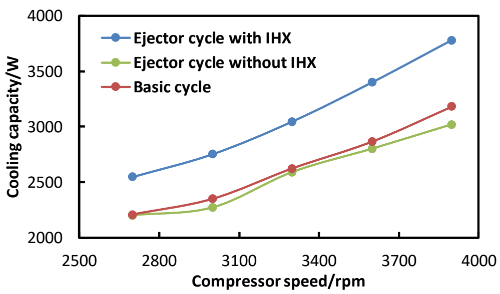
Fig 5 The performance of the system and the ejector for different opening degree of EEV

evaporator outlet and the outlet fluid gets smaller, as shown in Fig. 5(d).

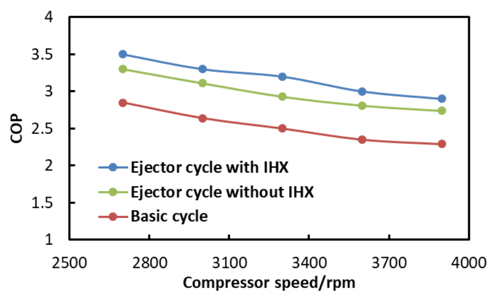
3.3 The effect of compressor speed

The compressor speed plays an important role in the capacity and the performance of refrigeration system. To investigate its impact on the ejector-expansion system, the test is operated with compressor speed varies from

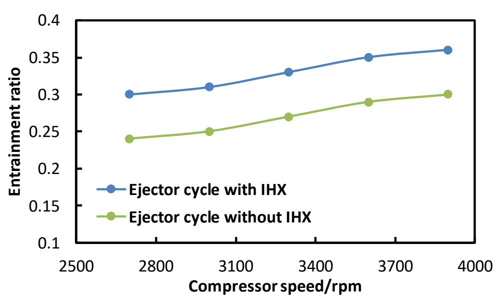
2700 rpm to 3900 rpm. As shown in Fig.6, the cooling capacity increases significantly for all of the three cycles. This is largely because the mass flow rate of the secondary fluid increases. On the other hand, larger mass flow means more work, resulting in the COP of the



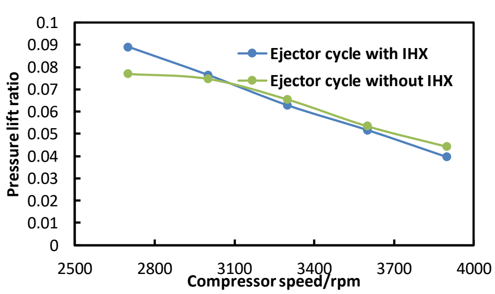
(a) Cooling capacity



(b) COP



(c) Entrainment ratio



(d) Pressure lift ratio

Fig 6 The performance of the system and the ejector for different compressor speed

ejector-expansion system reduces by 12.0 % as the compressor speed increasing. The result suggests that both the capacity and COP should be taken into consideration to get an optimal speed. Compared to the basic cycle, the ejector system can improve the performance both in capacity and COP, with a 18.7% increment in capacity and 26.6% in COP, respectively.

The entrainment ratio increases from 0.3 to 0.5 as the compressor speed increasing, as shown in Fig. 6(c). Benefitted from the IHX, the entrainment ratios get a significant improvement, increasing by 20%. This mainly because the introduction of the IHX can cool down the primary fluid, which is correspond to the contents of Section 3.1. The pressure lift ratio shows an apparent downward trend as the increasing in compressor speed. The decrease in PLR is mainly due to the decrease in the suction pressure.

4. CONCLUSIONS

This study investigates on the performance characteristics of a CO_2 ejector-expansion system applied for battery pack cooling. The performance of the system is analyzed under various gas cooler outlet temperature, EEV opening and compressor speed. The main conclusions are drawn as follows:

(1) The cooling capacity and COP decrease along with the outlet temperature of gas cooler increasing. The COP increases first and subsequently decreases with the increase in the EEV opening. The optimal opening degree of EEV is 39.3%.

(2) Compared with the basic cycle, ejector-expansion system can improve the performance both in capacity and COP significantly, a maximum 21.7% increment in cooling capacity and a maximum 28.0% increment in COP, respectively.

(3) Introducing an IHX before the compressor can improve the entrainment ratio of the ejector significantly. Both performance of the ejector and system should be taken into consideration to determine the selection of IHX.

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