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Comprehensive experimental study on a transcritical CO_2 ejector-expansion refrigeration system

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ABSTRACT

A comprehensive experimental study on the ejector and cooling performances of a transcritical CO_2 ejector-expansion system is presented. The ejector performance of the entrainment ratio, pressure lift ratio, and efficiency were investigated under various primary flow pressure, secondary flow pressure, and back pressure conditions. A new coefficient of mass balance, β, was introduced based on the liquid mass balance in and/or out of the vapor–liquid separator, which was able to estimate the deviation between current operating state and a steady state. The experiment results show that the coefficient of performance (COP) ratio of the ejector-expansion refrigeration system to the basic system decreases from 18.9% to −11% with the coefficient of mass balance increasing from −0.1 to 0.1. Both the entrainment ratio and COP decrease with an increase in the coefficient of mass balance.

1. Introduction

Carbon dioxide has the potential to replace CFCs and HCFCs in air conditioning systems, and has been receiving increasing attention. Experiment results have shown that CO_2 heat pump water heaters can have a relatively high outlet water temperature and superior efficiency because CO_2 has a high-temperature glide during the cooling process [1–3]. Compared to the wide use of HFC and HCFC refrigerants, CO_2 has a lower critical temperature. Thus, the transcritical mode is required when CO_2 refrigeration is used in a warm climate area. In a conventional transcritical CO_2 refrigeration system, the vapor quality in the expansion valve is high, which causes high throttle loss. Ejectors can be used to recover the expansion losses to increase the system efficiency. Ejectors have been studied over the past decades, mostly using working fluids of air, steam, and CFC, HCFC, and HFC refrigerants [4–6].

Previous studies on transcritical CO_2 ejector-expansion refrigeration systems have mainly been concerned with the ejector performance, structural impact, modeling methods, and refrigeration system performance and optimization. The advantage of using ejectors in transcritical CO_2 refrigeration systems has been verified both theoretically and experimentally. Many researchers using simulation analyses have reported that the coefficient of performance (COP) of the ejector expansion transcritical CO_2 cycle can be about 20% higher than that of a basic transcritical CO_2 cycle [7–11].

Chen et al. [12] experimentally investigated the ejector entrainment performance in a CO_2 ejector-expansion refrigeration rig under many different off-design conditions. The authors analyzed the effects of the primary flow pressure, entrained flow pressure, and back pressure on the ejector entrainment ratio. Nakagawa et al. [13] studied the effects of the mixing length on the ejector in the transcritical CO_2 cycle. Their experiment results showed that the improper sizing of the mixing length lowers the COP by as much as 10% compared to similar conventional systems. Liu et al. [14,15] experimentally studied the effects of different ejector geometries and operating conditions on the CO_2 ejector performance. The authors provided correlations of the motive nozzle efficiency, suction nozzle efficiency, and mixing section efficiency based on their experiment data.

Smolka et al. [16] studied a performance comparison of fixed- and controllable-geometry ejectors equipped with convergent and convergent-divergent nozzles installed in a CO_2 refrigeration system. The results show that, in most cases, the efficiency of the controllable-geometry ejector was 25% higher than that in the fixed-geometry case when the motive nozzle throat was reduced by approximately 35%. More recently, Palacz et al. [17] presented a shape optimization method of a CO_2 ejector considering six geometrical parameters. Their optimization improves the ejector efficiency by 6%.

Because the ejector is very sensitive to its operating conditions, the ejector off-design performance and the system transient performance are significant in real applications. Zheng et al. [18] and He et al. [19]

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Nomenclature

D	diameter, mm
h	enthalpy, kJ kg^{-1}
m	mass flow rate, kg s^{-1}
P	pressure, MPa
s	entropy, kJ kg^{-1} K^{-1}
T	temperature, K
x	fraction in mass, %

Greek letters

β	the coefficient of liquid mass balance in the vapor-liquid separator
ω	entrainment ratio, m_S/m_P
Π	the ratio of the pressure at the ejector outlet to the secondary flow inlet pressure
η_{eje}	the ejector efficiency

Subscripts

B	ejector outlet
P	primary flow at the nozzle inlet
S	secondary flow at the ejector inlet

developed dynamic models of the transcritical CO_2 ejector expansion refrigeration cycle, which can be used to analyze the dynamic responses of the system performance.

The flow field distribution is very important for describing the complex phenomena in transcritical CO_2 ejectors. However, information regarding the flow field inside the ejector is limited through such analytical modeling or performance experiments. Recently, a numerical method and a flow visualization technique have been applied to CO_2 ejectors. Numerical investigations into a CO_2 ejector showed oblique shock waves and temperature and pressure distributions based on a homogeneous equilibrium assumption [20,21]. Zhu et al. [22] used a flow visualization technique to visualize the flow fields in a suction chamber and mixing chamber of a CO_2 ejector for various operating conditions. The expansion angles and mixing phenomenon were analyzed in their experiments.

Many different modeling and experimental studies on an ejector-expansion transcritical CO_2 refrigeration system have been conducted to understand the operation of the system and improve its COP. Bai et al. [23] investigated an ejector-expansion transcritical CO_2 refrigeration system based on an exergy analysis, the results of which indicate that the compressor shows the largest avoidable endogenous exergy destruction in comparison with the ejector, evaporator, and gas cooler. Several two-stage transcritical CO_2 heat pump cycles have been proposed to further reduce the throttling loss and thus enhance the cycle performance, which also have an advantage of obtaining dual refrigeration temperatures [24–26]. The combination of a CO_2 vapor compression system with an ejector system has also been suggested [27,28], the purpose of which is to utilize the waste heat from the exhaust gas of the CO_2 compressor to drive the ejector system. An internal heat exchanger may be of benefit in terms of improving the COP of the ejector-expansion system of a trans-critical CO_2 refrigeration cycle. Several studies have reported the effects of an internal heat exchanger on the cooling performance of the ejector-expansion trans-critical CO_2 refrigeration cycle, and the results indicate that the COP is improved under certain operating conditions [29–31].

Lee et al. found that the ejector entrainment ratio is a key factor in an ejector expansion system [32,33]. Their results show that the cooling capacity and COP of an ejector expansion system are higher than those of a conventional system at entrainment ratios of greater than 0.76, where the cooling capacity and COP were about 2–5% and 6–9% higher than those of a conventional system. Lucas and Koehler [34] conducted an experimental study on an ejector refrigeration cycle, where the ejector efficiency, entrainment ratio, and pressure recovery from the ejector were investigated and a maximum COP improvement in the ejector cycle of 17% was reached with an ejector efficiency of up to 22%. The experiment results by Elbel and Hrnjak [35] showed that the ejector can improve the COP by up to 7% over a conventional system, and suggested that a diffuser with a small angle of 5° improves the static pressure recovery.

Banasiak et al. [36] experimentally investigated a multi-ejector expansion pack to replace a high-pressure electronic expansion valve, the ejector efficiency of which exceeds 0.3 over a broad operation range. The high-side pressure of a transcritical CO_2 ejector-expansion refrigeration system has an optimal value for different operating conditions and ejector geometries [9,37]. In addition, Xu et al. [38] experimentally investigated a transcritical CO_2 heat pump cycle with an adjustable ejector, and their results showed that the optimum high-side pressure increases with an increase in the gas cooler outlet temperature with an ejector efficiency of within 20–30%.

The entrainment and efficiency of a CO_2 ejector have been confirmed as key factors in a transcritical CO_2 ejector-expansion system. In this paper, a comprehensive experimental study on the performance of an ejector and a transcritical CO_2 ejector-expansion refrigeration system is presented. The ejector performance in terms of the entrainment ratio, pressure lift ratio, efficiency, and coefficient of the liquid mass balance were investigated under various primary flow pressure, secondary flow pressure, and back pressure conditions. In addition, the influence of the ejector performance on the COP of the system was analyzed.

2. Experiment setup and analysis method

2.1. Experiment system

A schematic of the transcritical CO_2 ejector-expansion refrigeration rig used in the present investigation is shown in Fig. 1. The system mainly consists of a compressor, a gas cooler, an evaporator, an ejector, a vapor-liquid separator, and an oil separator. The ejector functions as an expansion device. A needle valve, V2, is used to maintain a small pressure difference between the evaporator inlet and ejector outlet. The

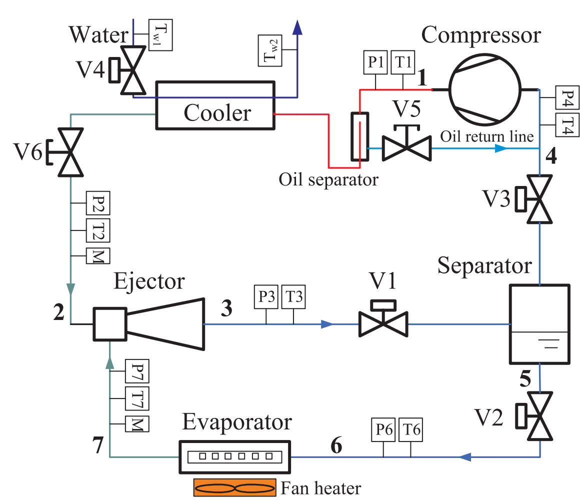

Fig. 1. Schematic of CO_2 ejector-expansion refrigeration system.