International Journal of Refrigeration 86 (2018) 218–227

Contents lists available at ScienceDirect

International Journal of Refrigeration

journal homepage: www.elsevier.com/locate/ijrefrig

Theoretical model of transcritical CO_2 ejector with non-equilibrium phase change correlation

Yinhai Zhu*, Peixue Jiang

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Beijing Key Laboratory of CO_2 Utilization and Reduction Technology, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 27 July 2017
Revised 25 October 2017
Accepted 26 October 2017
Available online 7 November 2017

Keywords:
Ejector
Carbon dioxide
Transcritical cycle
Model
Non-equilibrium

ABSTRACT

A theoretical model of an ejector was proposed for a transcritical carbon dioxide ejector-expansion refrigeration system capable of predicting the mass flow rates of both primary and secondary flows. A non-equilibrium correlation in the energy-conservation equation was proposed and validated using 130 cases obtained from three different ejector configurations. The differences in the predicted primary mass flow rates between the cases with and without the correlation were insignificant when the liquid mass fraction at the nozzle throat x_t was less than 0.65. However, the prediction error increases dramatically when the correlation was not used for $x_t > 0.65$. The Mach number in the CO_2 ejector is lower than 1.5 and the "double choking" phenomenon will not happen in the CO_2 ejector. Finally, a correlation was fitted for the primary flow pressure at the nozzle throat, which can be used to replace iterative solving in the model calculation.

1. Introduction

Heat-pump water heaters using CO_2 have a relatively high outlet-water temperature and a superior efficiency, because CO_2 has a high-temperature glide during a cooling process (Austin and Sumathy, 2011; Ma et al., 2013; Zhang et al., 2015). The transcritical cycle is preferred when CO_2 refrigeration systems are employed in warm climate areas because of its lower critical temperature. In a conventional transcritical CO_2 refrigeration system, the vapor quality in the expansion valve is high, causing high throttle loss. Ejectors can be used to recover the expansion losses to increase the system efficiency, which has been verified theoretically and experimentally (Ahammed et al., 2014; Deng et al., 2007; Jeong et al., 2004; Li and Groll, 2005; Sun and Ma, 2011).

Elbel and Hrnjak (2008) conducted an experimental study wherein the ejector helped in improving the COP by up to 7% over a conventional system. Lucas and Koehler (2012) experimentally studied an ejector-expansion refrigeration cycle. They improved the COP of the ejector cycle to a maximum of 17%. Lee et al. demonstrated that the entrainment ratio of the ejector was a key factor in an ejector-expansion system (Lee et al., 2011, 2014). The results showed that the cooling capacity and COP of the ejector-expansion system were approximately in the ranges of 2–5% and 6–9%, respectively, higher than those of a conventional system for entrainment ratios greater than 0.76.

Many studies have been conducted on the transcritical CO_2 ejector-expansion refrigeration system to understand its operating conditions and improve the COP (Banasiak et al., 2015; Elbel, 2011; Xu et al., 2012). Bai et al. (2016) conducted an exergy analysis to investigate an ejector-expansion transcritical CO_2 refrigeration system. The results showed that the compressor exhibited the highest avoidable endogenous exergy destruction compared to other components. Two-stage transcritical CO_2 heat-pump cycles are advantageous in obtaining dual-refrigeration temperatures and can help in reducing the throttling loss to a greater extent, and thus, enhance the cycle performance (Bai et al., 2015; Xing et al., 2014; Yari and Mahmoudi, 2011). To utilize the waste heat from the exhaust gas of a CO_2 compressor to drive the ejector system, hybrid systems were suggested (Chen et al., 2017, 2013a). Previous studies show that an internal heat exchanger might help in improving the COP of an ejector-expansion transcritical CO_2 refrigeration cycle (Goodarzi et al., 2015; Nakagawa et al., 2010; Zhang et al., 2013).

The ejector is the key component in the transcritical CO_2 ejector-expansion refrigeration system. The flow and mixing process inside the ejector are critically important for the design and performance prediction. The study on ejectors has been conducted for decades using experimental, theoretical, empirical, and numerical methods, largely with working fluids such as air, steam, and

* Corresponding author.
E-mail addresses: yinhai.zhu@tsinghua.edu.cn (Y. Zhu), jiangpx@mail.tsinghua.edu.cn (P. Jiang).

https://doi.org/10.1016/j.ijrefrig.2017.10.033
0140-7007/

Nomenclature

A	area, m^2
D	diameter, mm
h	enthalpy, J kg^{-1}
m	mass flow rate, kg s^{-1}
P	pressure, MPa
Q_{NE}	non-equilibrium correlation, J kg^{-1}
s	entropy, J kg^{-1} K^{-1}
T	temperature, K
V	velocity, m s^{-1}
x	fraction in mass, %

Greek letters

a	speed of sound, m s^{-1}
ρ	density, kg m^{-3}
φ	efficiency
ω	entrainment ratio, m_S/m_P

Subscripts

B	ejector outlet
d	diffuser
m	mixing chamber
n	nozzle
l	liquid phase
P	primary flow at the nozzle inlet
pm	primary flow at the mixing chamber inlet
S	secondary flow at the ejector inlet
sm	secondary flow at the mixing chamber inlet
t	nozzle throat
v	vapor phase

CFC, HCFC and HFC refrigerants (Besagni et al., 2016; Chen et al., 2015, 2013b).

The ejector in a transcritical CO_2 ejector-expansion refrigeration system has a two-phase flow inside and a smaller pressure-recovery ratio compared to ejectors using other working fluids. The flow field distribution is very important to explain the complex phenomena occurring in the CO_2 ejectors. Numerical investigations were conducted on a CO_2 ejector wherein oblique shock waves and temperature and pressure distributions were obtained by assuming a homogeneous equilibrium (Bodys et al., 2017; Lucas et al., 2014). Recently, Zhu et al. (2017a) experimentally visualized the flow fields in the suction and mixing chambers of a CO_2 ejector using a flow-visualization technique. The shock of the primary flow while expanding in the suction chamber was relatively weak compared to that in a low-pressure working-fluid ejector (Zhu and Jiang, 2014a,b).

The performance of the ejector depends on its geometry and operating conditions. Nakagawa et al. (2011) studied the effect of the mixing length on the ejector in a transcritical CO_2 cycle. The experimental results showed that an improper size of the mixing length lowered the COP by as much as 10% compared to that in similar conventional systems. Liu et al. (2012a) and Liu and Groll (2012b), experimentally studied the effects of different ejector geometries and operating conditions on the performance of a CO_2 ejector. They found that the ejector reaches its optimum performance at particular values of the throat diameter, mixing-section constant-area diameter, and diffuser diameter. Smolka et al. (2016) compared the performances of fixed and controllable-geometry ejectors equipped with convergent and convergent–divergent nozzles installed in a CO_2 refrigeration system. The results showed that in most cases, the efficiency of the controllable-geometry ejector was 25% higher than that of the fixed-geometry ejector. More recently, Palacz et al. (2017) presented a shape-optimization method for the CO_2 ejector considering six geometrical parameters including the primary nozzle and mixing section.

Several theoretical and numerical models have been developed for the ejector with a transcritical CO_2 working fluid. Chen et al. (2010) used “characteristic-curve equations” to evaluate the entrainment ratio of the ejector. The validation results showed that the calculated entrainment ratio was higher than that of the experimental data, because a single-phase flow was assumed. Banasiak and Hafner (2011) presented a one-dimensional mathematical model of the CO_2 two-phase ejector with a delayed equilibrium model including a homogeneous nucleation theory, which was validated for a typical range of operating conditions. The absolute values of the relative errors between the experimental and simulation results for both the overall pressure lift and the critical primary mass flow rate were 2.66% and 1.84% on average, respectively. However, the performance of the model in predicting the mass flow rate of the secondary flow was not reported. Liu et al. (2012a) proposed a CO_2 ejector model under the assumption of a one-dimensional one-component homogeneous equilibrium two-phase flow. They showed that the simulation model helped in predicting the mass flow rate of the primary flow within an error of 2% of the measured data. However, they did not compare the mass flow rates of the secondary flow between the calculated and experimental values. Smolka et al. (2013) developed a mathematical model for a compressible transonic two-phase flow of a real fluid, wherein the temperature-based energy equation was replaced with an enthalpy-based equation. The main advantage of the developed model is its numerical robustness compared to the Euler–Euler or mixture models. Zheng et al. (2016) developed dynamic models for the transcritical CO_2 ejector-expansion refrigeration cycle, which can be used to analyze the dynamic responses of the system performance. The model was validated under two steady conditions and was in good agreement with the experimental data.

Predicting the mass flow rate of the secondary flow is important and is more complicated than predicting the primary mass flow rate, particularly when the ejector is operated in the subcritical mode. In this study, a theoretical model of the transcritical CO_2 ejector was proposed capable of predicting the mass flow rates of both the primary and secondary flows. We considered the non-equilibrium phase change effect in the flow passing through the nozzle. A non-equilibrium correlation for the energy conservation equation was obtained, which was validated using 130 cases obtained from three ejector configurations. The velocity and mass fraction inside the ejector were analyzed under various primary flow pressures, secondary flow pressures, back pressures, and primary flow inlet temperatures. Finally, we developed a correlation for the primary flow pressure at the nozzle throat, which can be directly used in modeling the ejector.

2. Experimental setup

2.1. Experimental system

Two different ejectors were tested on a transcritical CO_2 ejector-expansion refrigeration rig as shown in Fig. 1. The system comprises a compressor, a gas cooler, an evaporator, an ejector, a vapor–liquid separator, and an oil separator, which was developed by Zhu et al. (2017a).

The compressor used was a DORIN CD180H with a rated displacement of 1.12 m^3 h^{-1} at 380 V/50 Hz. A 7.5 kW inverter was used to control the compressor speed. The gas cooler was a counter-flow plate heat exchanger with water as the coolant. The designed capacity of the gas cooler was 7.5 kW. The evaporator was a parallel-flow microchannel heat exchanger with a variable-speed fan to control the outflow superheat of the evaporator. The