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A novel transcritical CO_2 refrigeration cycle with two ejectors

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ABSTRACT

In recent years, CO_2 is being revisited as a fully environmentally friendly and safe refrigerant. However, basic CO_2 transcritical refrigeration cycle suffers from large expansion loss due to high pressure difference between gas cooler and evaporator. Then, it is crucial to find effective and economic way to reduce the expansion loss. Here, a novel cycle with two ejectors is proposed for the first time. Compared with conventional ejector-expansion CO_2 cycle with only one ejector, this novel cycle with two ejectors is able to recover more expansion loss, thus improving the system performance further. A computational model is designed to simulate the double ejector CO_2 cycle. Simulation results show its high system COP. Effects of parameters, such as ejector nozzle efficiency, gas cooler pressure, entrainment ratios of the two ejectors, gas cooler outlet temperature, on the cycle performance are also analyzed by using the computational model.

Nouveau cycle frigorifique au CO_2 transcritique employant deux éjecteurs

Mots clés : Dioxyde de carbone ; R744 ; Cycle transcritique ; Éjecteurs ; Modélisation ; COP

1. Introduction

Carbon dioxide is a promising refrigerant due to its environment-benign nature (Lorentzen, and Pettersen, 1990; Kim et al., 2004). However, previous literature (Elbel and Hrnjak, 2008; Li and Groll, 2005; Nickl et al., 2005; Robinson and Groll, 1998; Sarkar et al., 2005, 2008, 2009; Yang et al., 2009; Yari, 2009) have reported that high pressure drop in basic transcritical CO_2 refrigeration cycle results in much larger thermodynamic expansion loss compared to conventional refrigeration cycles.

In order to recover throttling loss, several measures have been proposed. Replacement of the expansion valve by an expander (Robinson and Groll, 1998; Nickl et al., 2005; Yang

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Nomenclature

a	area per unit total ejector flow rate
COP	coefficient of performance
h	specific enthalpy
m	mass flow rate
P	pressure
Q	heat capacity
q	specific heat capacity
R	relative performance
s	specific entropy
t	temperature
u	velocity
v	specific volume
W	work load
x	quality

Greek symbols

η	isentropic efficiency
ω	entrainment ratio of the ejector

Subscripts and superscripts

b	receiving chamber or basic transcritical CO_2 cycle
comp	compressor
d	diffuser
drop	pressure drop in the receiving section of the ejector
e	evaporator
f	saturated liquid
g	saturated vapor
gc	gas cooler
is	isentropic process
m	motive nozzle
mb	motive flow at receiving chamber
mi	motive flow at nozzle inlet
mix	outlet of mixing section
n	ejector expansion transcritical CO_2 cycle
o	outlet
s	suction nozzle
sb	suction flow at receiving chamber
sh	superheat
si	suction flow at nozzle inlet
I	the first ejector
II	the second ejector

et al., 2009) is a direct measure. Although replacing the expansion valve with a turbine can significantly improve the performance of CO_2 transcritical cycle, such extensive hardware addition may not be economically feasible for many practical applications, especially for small capacity CO_2 cycle (Sarkar et al., 2005). Other measures include using ejector-expansion device (Sarkar et al., 2005; Li and Groll, 2005; Sarkar, 2008; Elbel and Hrnjak, 2008; Yari, 2009; Robinson and Groll, 1998; Yang et al., 2009; Sarkar, 2009) or vortex tube (Sarkar, 2009) to replace the expansion valve. This ejector-expansion device has advantages, such as low cost, no moving parts and ability to handle two-phase flow without damage, making it attractive for the development of high-performance CO_2 refrigeration system (Yari, 2009).

Li and Groll (2005) performed a thermodynamic analysis with respect to a transcritical CO_2 cycle of different expansion devices. It was found that the COP of the ejector-expansion transcritical CO_2 cycle can be improved by more than 16% over the basic transcritical CO_2 cycle for typical air conditioning operation conditions. Sarkar (2008) presented an optimization study along with optimum parameter correlations, using constant area mixing model (Li and Groll, 2005) for an ejector-expansion transcritical CO_2 heat pump cycle with either conventional or modified layout. He pointed out that the ejector may be the best alternative expansion device at least for low-capacity transcritical CO_2 heat pump systems. Elbel and Hrnjak (2008) conducted experimental validation of a prototype ejector designed to reduce throttling losses encountered in transcritical CO_2 system operation. Their experimental results showed that for the best conditions considered, the cooling capacity and COP were simultaneously improved by up to 8% and 7%, respectively.

Under typical air-conditioning operation conditions, the pressure difference across the throttling valve is reduced from 6 to 7 MPa for basic CO_2 cycle to about 3–4 MPa for the CO_2 cycle with one ejector. However, compared with R134a or R22 cycle, 3–4 MPa pressure difference across the throttling device is still quite large. That is to say, there is still a lot of expansion loss needs further recovering. Thus, to solve this problem we propose a double ejector-expansion CO_2 cycle in the present paper for the first time. The expansion loss will be recovered twice in this novel double ejector-expansion CO_2 cycle and COP may be further improved compared with conventional single-ejector cycle.

To understand the characteristics of the novel double ejector-expansion CO_2 cycle, we adopt the ejector model of Li and Groll (2005) for the thermodynamic simulation of the new cycle. Effects of some parameters on the performance of this new cycle are theoretically analyzed.

2. Double ejector-expansion CO_2 transcritical cycle layout

Based on the single-ejector cycle proposed by Li and Groll (2005), a double-ejector cycle, schematically shown in Fig. 1, is proposed. The p-h diagram of this cycle is depicted in Fig. 2. The cycle is composed of a compressor, a gas cooler, two ejectors (ejector I and ejector II), two separators (separator I and separator II), four throttling valves and an evaporator. The working process of the cycle is described in detail as follow:

One unit mass of compressed CO_2 stream in supercritical state is introduced into a gas cooler. The cooled-down stream then enters ejector I as the primary flow to eject ω_1 unit mass of low-pressure fluid from separator II. The $1 + \omega_1$ unit mass of fluid mixes and passes the diffuser of ejector I and flows into separator I. Due to the reason described by Li and Groll (2005), the quality (χ_1) of separator I must be larger than the mass flow rate of the stream sucked into the compressor to