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Experimental analysis on the effect of internal heat exchanger in transcritical CO_2 refrigeration cycle with two-phase ejector

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ABSTRACT

The performance of CO_2 ejector refrigeration system needs further improvement to make CO_2 more viable than traditional harmful refrigerants. In this research, the effect of internal heat exchanger (IHX) in the performance of ejector refrigeration system was analyzed experimentally and compared with conventional expansion refrigeration system. Experiments were performed at different operating pressure and temperature for the cases of without IHX, 30 cm IHX and 60 cm IHX. The results showed that IHX significantly increased the coefficient of performance (COP) of ejector system. At the conditions used in this research, the ejector system with 60 cm IHX provided the maximum COP improvement of up to 27% compared to similar conventional system. The motive nozzle's inlet condition had significant effect on the performance of ejector system. The results also confirmed the presence of considerable amount of liquid refrigerant at separator's gas outlet of ejector system which was deemed possible in our previous research.

Analyse expérimentale d'un échangeur de chaleur interne dans un cycle frigorifique au CO_2 à éjecteur diphasique

Mots-clés : Système frigorifique ; Système à compression ; Système à éjecteur ; Dioxyde de carbone ; Cycle transcritique ; Échangeur de chaleur ; Expérimentation - performance

1. Introduction

The HVAC and refrigeration industry plays a major role in dealing with the worsening problem of global warming and ozone depletion. The natural refrigerant carbon dioxide, also known as refrigerant R744, is one of the most promising alternative refrigerants because it has zero ozone depletion potential and very low global warming potential. However, its application in transcritical conventional refrigeration system induces significant energy loss mainly caused by the fluid

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Nomenclature

COP	coefficient of performance [–]
$\dot{m}$	nozzle mass flow rate [kg s^{-1}]
g	entrainment ratio [–]
h	specific enthalpy [J kg^{-1}]
IHX	internal heat exchanger
P	pressure [Pa]
$\dot{Q}$	capacity [W]
s	specific entropy [J kg^{-1} K^{-1}]
T	temperature [°C]
$\dot{W}$	work rate [W]
x	quality [–]
v	specific volume [m^3 kg^{-1}]
η	efficiency [–]

Subscripts

c	gas cooler
comp	compressor
mn	motive nozzle
e	evaporator
eje	ejector
s	suction inlets
n	suction nozzle
var	variable

expansion from above critical point to two-phase state. This energy loss can be recovered by using a two-phase ejector. The available kinetic energy from the expansion process is utilized to provide higher inlet pressure to the compressor which improves the COP of the system

The idea of ejector was conceptualized in the early 1900s by Parsons and the first ejector prototype for steam jet application was built by Leblanc in 1910 (Gosney, 1982). Gay (1931) and Kemper et al. (1966) patented their own ejector designs after some modifications. Keenan and Neumann (1942) used basic conservation equations using ideal air as the fluid to formulate one of the earliest ejector theories. Keenan et al. (1950) later modified it by using a constant pressure mixing process. Nakagawa et al. (1994) performed a theoretical analysis on the mixing performance of two-phase ejector using R-12 and verified it experimentally. Harrel and Kornhauser (1995) performed an experimental analysis on ejector system but they reported a significant low improvement in actual COP compared to the ideal COP computed by Kornhauser (1990). Nakagawa and Takeuchi (1998) performed an experimental analysis of R134a ejector system and obtained a 10% improvement in COP compared to conventional system. Huang et al. (1999) developed a one-dimensional analysis of the ejector using R141b and reported a model accuracy of ±15% compared to experimental data. These cited literatures had used steam or Freon-based refrigerants as their working fluid. There are relatively few available researches which used the natural refrigerant CO_2 and most of these were only theoretical analysis without or with limited experimental verification. Morimune and Nakagawa (2002) performed a theoretical analysis on CO_2 ejector system and reported promising benefits in using the natural refrigerant CO_2. Li and Groll (2005) and Deng et al. (2007) also carried out theoretical investigations and concluded that up to 22% improvement, based on the operating parameters they used in their research, can be achieved using CO_2 ejector refrigeration system. Further improvement in the COP of CO_2 ejector system is desirable to prove its viability against the classical Freon-based refrigerants. One way of achieving this is to design a more efficient ejector. We have published several researches about the dynamics and improvements of the motive nozzle of the two-phase ejector using CO_2 (Nakagawa and Morimune, 2003; Nakagawa et al., 2004). Sarkar (2008) published an optimization study on the effect of operating parameters to ejector performance. In conventional refrigeration system, IHX is used to improve the performance of the system. The applicability of IHX in CO_2 ejector refrigeration system is not well researched. The objective of this research is to provide experimental analysis on the performance of CO_2 refrigeration with and without IHX for both ejector and conventional systems at different operating conditions. There were published experimental data about the performance of CO_2 refrigeration cycle with IHX but those studies were limited to conventional expansion system (Kim et al., 2005; Cho et al., 2007; Aprea and Maiorino, 2008). To the best knowledge of this author, only Elbel and Hrnjak (2008) performed experimental analysis on CO_2 ejector refrigeration with IHX and reported a 7% increase in COP over conventional system. However, they only published relatively few experimental data on the performance of ejector cycle using IHX.

We have been performing experimental study on the dynamics and performance of CO_2 ejector refrigeration system. Based on our previous experimental data (Nakagawa et al., 2009), there is a possibility that a considerable amount of liquid refrigerant from the separator flows through the compressor inlet which can be prevented with the use of IHX. This possibility can also be confirmed experimentally using IHX which is another objective of this study.

2. Thermodynamic analysis of ejector cycle with and without internal heat exchanger

It is a common practice to use internal heat exchanger in conventional refrigeration system to increase the cooling capacity of the system. The refrigerant flowing to the compressor inlet exchanges heat with the fluid flowing out of the gas cooler. In effect, the temperature of the refrigerant upstream of the expansion valve decreases while the compression work increases because of higher compressor inlet temperature at the same inlet and outlet pressure. The location of IHX for the case of ejector system is similar to a conventional cycle where the fluid flowing out of the gas cooler also exchanges heat with the fluid flowing to the compressor inlet, as shown in Fig. 1. In effect, the refrigerant enters the motive nozzle at lower temperature while the inlet of compressor is at superheated state. The P–h diagrams of both ejector cycles with and without IHX are shown in Fig. 2. The gas cooler pressure P_c, gas cooler exit temperature T_c and evaporator temperature T_e for this diagram are 10 MPa, 40 °C and 0 °C, respectively. The