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Performance analysis of the ejector-expansion refrigeration cycle using zeotropic mixtures

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ABSTRACT

To evaluate the performance of the ejector-expansion refrigeration cycle (EERC) using zeotropic mixtures, a numerical study is conducted. A constant-pressure two-phase ejector model for zeotropic mixtures is established. The effects of both the fluid composition and the working conditions are investigated. Mixture R134a/R143a is selected as the working and the simulation results reveal that, the cycle COP increases first and then decreases as MF_t (the mass fraction of R134a) increases in the researched condition. The COP gets a maximum value of 4.18 with MF_t of 0.9 and yields a minimum value of 3.66 with MF_t of 0.5. With mixture 0.9/0.1, the COP improvement reaches a maximum value of 10.47%. This improvement rises at high condensing temperature or low evaporating temperature. The exergy analysis shows that the compressor and ejector contribute the most exergy destruction, and the cycle exergy efficiency achieves a maximum value with MF_t of 0.7.

Analyse de la performance du cycle frigorifique à détente par éjecteur utilisant des mélanges zéotropiques

Mots-clés : Cycle frigorifique à détente par éjecteur ; Mélanges zéotropiques ; Diphasique

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Nomenclature

Symbols

COP	coefficient of performance
EERC	Ejector-Expansion Refrigeration System
h	specific enthalpy, kJ kg^{-1}
m	mass flow rate, kg s^{-1}
MF	mass fraction of R134a
P	pressure, MPa
Q	heat load, kW
s	entropy, kJ kg^{-1} K^{-1}
T	temperature, K
u	velocity, m s^{-1}
W	work, kW
x	vapor quality

Greek letters

μ	entrainment ratio
η	efficiency

Subscripts

co	condenser or condensing
com	compressor
d	diffuser
ev	evaporator or evaporating
ej	ejector
i	improvement
mi	mixing flow or mixing section
n	nozzle
p	primary flow or primary nozzle
s	secondary flow
sp	separator
t	total
th	throttling valve

1. Introduction

In the traditional vapor compression system, capillary tube, thermostatic expansion valve and other throttling devices are applied to reduce the refrigerant pressure from the condenser to evaporator. Some methods are proposed to improve the refrigeration performance through recovering the energy of this process. Recently, several studies have been carried out considering two-phase ejector as an efficient way to reduce the throttling loss (Sumeru et al., 2012). Compared with the others, ejector has a lower cost and a simpler structure. Also, it has no moving component (Ersoy and Bilir Sag, 2014).

The idea of replacing throttle valve with a two-phase ejector as an expansion valve was first proposed in a patent by Gay (1931). However, the first numerical analysis on the ejector-expansion refrigeration cycle (EERC) was proposed until 1990 by Kornhauser (1990). It was found that the EERC has a great potential for a significant improvement over the standard vapor compression refrigeration cycle (VCRC). Seven refrigerants were investigated: R11, R113, R114, R500, R502, R22 and R717. And R502 yields the largest COP improvement over VCRC, as large as 30%.

Disawas and Wongwises (2004) carried out an experiment on EERC with R134a. It was proved that compared with the VCRC, the EERC had a larger COP under all the investigated conditions. But the improvement dropped with a heat sink temperature increasing. In their following work, Wongwises and Disawas (2005) found that the EERC has a larger COP and a higher refrigeration capacity. Besides, the evaporator has a higher refrigerant-side heat transfer coefficient as the EERC enables the evaporator flooded with refrigerant. With the same test rig, Chaiwongsa and Wongwises (2007) investigated the effect of throat diameter on the EERC performance. Ejectors with three throat diameters, 1.0 mm, 0.9 mm and 0.8 mm were tested. The result showed that the EERC achieved the highest COP when the throat nozzle diameter is 0.8 mm and the lowest COP when the diameter is 1.0 mm.

Nehdi et al. (2007) analyzed the effect of the ejector area ratio. They found that the maximum COP is obtained for Φ_{opt} whose value is around 10. Under the given operating conditions ($T_{co} = 50$ °C, $T_{ev} = -30$ °C), R141b achieved a maximum COP among twenty refrigerants, 22% higher than that of the VCRC. Bilir and Ersoy (2009) carried out a numerical analysis on the EERC and compared with VCRC. The COP improvement ranged from 10.1% to 22.34% in the researching condition, and it increased as the difference between the condenser and evaporating temperature rise. Recently, Hu et al. (2014) tested an adjustable liquid–gas ejector on R410A air conditioning system. The experimental results showed that the ejector with adjustable nozzle can improve the EERC performance. And the EERC could increases the energy efficiency ratio than VCRC as large as 9.1%.

In addition, some researchers found that the EERC could reduce the pressure drop in the evaporator. As the two-phase flow at the ejector exit was separated into two parts: saturated liquid and saturated vapor. The fluid that enters the evaporator was saturated fluid from the phase separator exit. However, in the conventional VCRC, the fluid enters the evaporator as two-phase state, causing a large pressure drop (Tuo and Hrnjak, 2014). Ersoy and Bilir Sag (2014) experimentally compared the performance of EERC and VCRC under the same external conditions. It was observed that the EERC had a COP 6.2–14.5% higher than that of the VCRC. The evaporating temperature was about 10 °C, and the condensing temperature varied from 52 °C to 60 °C. The EERC had a smaller pressure drop than the VCRC. Under the investigated condition, the pressure drop in the evaporator of the EERC was smaller than 4 kPa, but it was larger than 95 kPa for the VCRC. In the experimental study of Pottker and Hrnjak (2015), the performance of the EERC was researched to evaluate two major improvements of the EERC: work recovery and liquid-fed evaporator. The ejector-expansion refrigeration system was compared with two refrigeration systems using R410a. It was first compared with a flash gas bypass system with liquid-fed evaporator, and the result revealed that the COP improvement ranged from 4.9% to 9.0%. Compared with the standard vapor compression system, the ejector-expansion refrigeration system COP increase varied from 8.2% to 14.8%, with both contributions of liquid-fed evaporator and work recovery.

In these researches, the working fluids are all pure working fluids or azeotropes. The constant-temperature characteristic