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Investigation of a novel ejector expansion refrigeration system using the working fluid R134a and its potential substitute R1234yf

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ABSTRACT

To overcome the constraints related to the steady-state operation of the ejector and the separator in a basic ejector-expansion refrigeration system, a new refrigeration system with two evaporators using an ejector as a throttling valve is presented. A constant-area mixing model for the ejector requiring a small number of data and assumptions was established to perform a thermodynamic cycle analysis of the new system. The effects of the ejector area ratio and the condenser temperature on the performance of the ejector and therefore on the increase in COP of the new system compared to the conventional bi-evaporator refrigeration system were investigated for the same cooling capacities of the two evaporators. The refrigerants R134a and its substitute R1234yf were tested. It was found that the novel system has an important improvement in COP for both R134a and R1234yf. This increase in COP is higher for R1234yf especially at high condensing temperatures.

Etude d'un nouveau système frigorifique à détente par éjecteur utilisant le fluide actif R134a et son substitut potentiel R1234yf

Mots clés : Ejecteur ; Efficacité ; R134a ; R1234yf ; Modélisation ; Ecoulement diphasique

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Nomenclature

A	area of cross-section, m^2
a	sound speed, m s^{-1}
CBERS	Conventional Bi-Evaporator Refrigeration System
COP	coefficient of performance
D	diameter, m
EERS	Ejector-Expansion Refrigeration System
h	specific enthalpy, J kg^{-1}
Ma	Mach number
$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{m}_1$	mass flow rate of refrigerant in the evaporator 1 of the CBERS
$\dot{m}_2$	mass flow rate of refrigerant in the evaporator 2 of the CBERS
NEERS	Novel Ejector-Expansion Refrigeration System
P	pressure, Pa
$\dot{Q}$	refrigerating capacity, W
r	ejector compression ratio ($=P_{ev2}/P_{ev1}$)
s	specific entropy, J kg^{-1} K^{-1}
T	temperature, °C
U	mass flow rate ratio ($=\dot{m}_S/\dot{m}_P$)
V	velocity, m s^{-1}
v	specific volume, m^3 kg^{-1}
$\dot{W}$	mechanical work rate, W
x	vapor quality

Greek letters

η	isentropic efficiency
η_{ej}	compression efficiency of ejector
Φ	ejector area ratio ($=(D_m/D^*_P)^2$)
ρ	density, kg m^{-3})
ξ	ejector driving pressure ratio ($=P_C/P_{ev2}$)

Subscripts and superscripts

C	condenser
co	conventional
comp	compressor
d	diffuser
de	diffuser exit
e	exit
ej	ejector
ev1	evaporator1
ev2	evaporator2
f	fluid
g	gas
i	inlet
is	isentropic
m	mixing flow or mixing section
P	primary flow or primary nozzle
S	secondary flow or suction nozzle
sat	saturation
*	cross-section throat

1. Introduction

The refrigeration and air conditioning consume about 10–15% of the available electric energy. The depletion of fossil fuel resources and the various protocols for the protection of the environment have prompted the researchers to develop cooling systems allowing the use of waste heat of industrial processes (Chen, 2001; Boumaraf and Lallemand, 1999, 2009; Srikhirin et al., 2001) or a free energy source, such as solar energy (Wolpert and Riffat, 2002; Nguyen et al., 2001), and to propose solutions for improving the energy efficiency of conventional vapor compression systems.

This effort for fossil energy savings was accompanied by the replacement of synthetic refrigerants (CFCs, HCFCs and HFCs) by natural refrigerants such as CO_2, H_2O and NH_3 or by other synthetic fluids which are more respectful of the environment as the new refrigerant R1234yf (Minor and Spatz, 2008) which has a Low Global Potential and zero Ozone Depletion Potential (GWP = 4 and ODP = 0 according to the IPCC). R1234yf should replace R134a which has a high contribution to the greenhouse effect (GWP = 1430 according to the IPCC), especially in the automotive air conditioning systems. Besides, R1234yf has good thermophysical properties very similar to R134a. In addition, compared with the natural refrigerant CO_2, the advantages of R1234yf are that it can be directly charged into conventional refrigeration systems for instead of R134a with only minor modifications, and has a lower pressure and higher energy efficiency.

Minor and Spatz (2008) investigated the performance of R1234yf as an alternative to R134a in a mobile air conditioning system. Results show that with no system changes, the cooling capacity and COP of R1234yf are generally 4–8% lower than R134a performance. Analogous results were also reported by Zilio et al. (2011), Jarall (2012) and Ozgür et al. (2014). On the other hand, these researchers observe that at the same operating conditions, R1234yf has a lower compression ratio and discharge temperature relative to R134a. Navarro-Esbri et al. (2013a, b) present an experimental analysis of a vapor compression system using R1234yf as a drop-in replacement of R134a. The results show that the cooling capacity obtained with R1234yf is about 9% lower and values of COP are between 5 and 30% lower than those obtained with R134a. The experimental results also show that the differences in the values of cooling capacity and those of COP obtained with both refrigerants decrease when the condensing temperature increases and when an internal heat exchange is used.

This paper is focused on the vapor compression refrigeration cycle which is composed mainly by a compressor, a condenser, an evaporator and an expansion valve. It is used in most applications of refrigeration, air conditioning and heat pumps. During the expansion process, a significant portion of the kinetic energy due to the passage from high pressure to the low pressure is dissipated in the fluid. The process is then not isenthalpic and these losses reduce the cooling system efficiency. Many researchers have analyzed the cycle performance of the conventional refrigeration systems in order to identify opportunities to improve its energy