Energy 95 (2016) 144–154

Contents lists available at ScienceDirect

Energy

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

Thermodynamic analysis on a modified ejector expansion refrigeration cycle with zeotropic mixture (R290/R600a) for freezers

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form
27 November 2015
Accepted 29 November 2015
Available online 29 December 2015

Keywords:
Exergy
Freezers
Ejector refrigeration cycle
Zeotropic mixtures
R290/R600a

ABSTRACT

This study presents a modified ejector expansion cycle with zeotropic mixtures (R290/R600a) for freezers, in which an ejector and a phase-separator are employed to enhance the cycle performance. Energetic and exergetic methods are used to theoretically investigate the system operating characteristics. In addition, comparative research among the modified cycle, conventional ejector expansion cycle and basic throttling cycle is carried out. The results demonstrate that the modified cycle exhibits higher refrigeration COP (coefficient of performance), volumetric refrigeration capacity and system exergy efficiency than conventional ejector expansion cycle and basic throttling cycle. Under the given operation conditions, the system performance improvements of the modified cycle in terms of the COP, refrigeration capacity and system exergy efficiency over the basic throttling cycle could reach about 56.0%, 4.5% and 77.7%, respectively. The performance characteristics of the proposed cycle show its potential practical advantages in freezer applications.

1. Introduction

Currently, freezers have become popularity in commercial and residential applications due to its low refrigeration temperature and lower cost. Thus, energy saving technologies of freezers play a significant role on social energy saving and CO_2 emission reduction. In order to achieve higher energy utilization efficiency and effectively protect the global environment, various energy saving technologies for freezers have been developed in the past decades [1]. Adopting appropriate natural refrigerant with low GWP (global warming potential), such as CO_2 and hydrocarbons (propane, butane and isobutene), is one of the advanced methods of enhancing system performance and reducing ozone depletion and global warming [2–4]. Much work on the freezer cycles with pure or mixture natural refrigerant has been carried out [5–9]. From the open literature, it could be found that zeotropic mixture refrigerant (R290/R600a) attracts much attention in freezer cycle performance improvement due to its environmentally friendly properties and energy saving potential. As is known, the zeotropic mixtures refrigerant based refrigeration systems undergo Lonrenz cycle and thus exhibit large energy saving potential due to the temperature glide in the phase change in condenser and evaporator, leading a reduction in the irreversibility loss occurring the heat exchange process [10,11]. Therefore, it could be inferred that the zeotropic mixture refrigerant (R290/R600a) has considerable application potential in freezer cycles.

In addition, cycle modification can efficiently improve the performances of the refrigeration cycles [12]. In freezers with low refrigeration temperature, large pressure drop from condenser and evaporator indicates that much irreversibility exists in the system, which seriously reduces the system performance. Ejector is a proposed expansion device to replace the expansion valve or capillary tube and recover the expansion losses in the throttling process [12,13]. Therefore, cycle modification adopting ejector is a considerable method for enhancing the system performances for freezer cycles. However, from the open literature about refrigeration cycles with ejector, it could be found that the past work mainly focuses on the air conditioner cycles [14–17], heat pump cycles [18–20] and refrigerator–freezer cycles [21–23], and the commonly adopted refrigerants are near-azeotropic and pure refrigerants, such as R410A, CO_2 and R600a recently [23–27]. However, the investigations on ejector enhanced freezer cycles with zeotropic mixture refrigerant R290/R600a are not sufficient presently.

In this paper, a modified ejector expansion refrigeration cycle with zeotropic mixture R290/R600a (MERC) for freezers is proposed. In this cycle, the temperature variation of the zeotropic mixture R290/R600a in heat exchange processes at condenser and evaporator could well match the temperature glide of the

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http://dx.doi.org/10.1016/j.energy.2015.11.067
0360-5442/

Nomenclature

COP	coefficient of performance
$\dot{E}x$	exergy rate, kW
h	specific enthalpy, kJ/kg
$\dot{m}$	refrigerant mass flow rate, kg/s
P	pressure, MPa
Q_R	refrigeration capacity, kW
q_v	volumetric refrigeration capacity, kJ/m^3
r_P	pressure lift ratio
T	temperature, °C
u	velocity, m/s
v	specific volume, m^3/kg
W	compressor power, kW
z_{R290}	mass fraction of R290

Greek letters

η	efficiency
μ	entrainment ratio
π	compression ratio

Subscripts

Cm	compressor
Cn	condenser
Ct	capillary tube
d	diffuser
des	exergy destruction
e	evaporation
end	cold end at the internal heat exchanger
Ev	evaporator
Eje	ejector
i	inlet
is	isentropic process
IHX	internal heat exchanger
mix	mixing chamber
n	nozzle
o	outlet
p	primary fluid
s	secondary fluid
sys	system
Sc	subcooler
1–12	state point

secondary fluids (air), which could reduce the irreversibility loss and improve the system performance. What is more, and a phase separator is placed between two condensers to achieve partial condensation for the condensed fluid. In this case, the two saturated streams with different refrigerant compositions are obtained at the phase separator, and this composition shift feature offers the possibility to improve the system performance using appropriate cycle modification. In addition, an ejector is adopted to recover the expansion loss and strengthen the recirculation of the working fluid, aiming to enhance the system performance. Therefore, the modified cycle MERC would have performance improving potential. The objective of this paper is to theoretically evaluate the system thermodynamic performances of MERC cycle with energetic and exergetic methods [28,29]. The effects of the operating parameters including refrigerant composition ratio, evaporation temperature, condensation temperature and subcooling on the system performances are discussed. Additionally, in order to explore the operating characteristics of MERC cycle and exhibits its energy saving potential, comparative research among the modified ejector cycle, basic throttling refrigeration cycle with an internal heat exchanger (BTRC) is conducted and conventional ejector expansion refrigeration cycle with an internal heat exchanger (CERC) and, attempting to explore the application possibility of the MERC cycle in freezers.

2. Description of the system

To perform the thermodynamic performances of the proposed cycle (MERC), the schematic and pressure-enthalpy diagrams of the BTRC and CERC cycles are shown in Figs. 1 and 2, respectively. And the schematic and pressure-enthalpy diagrams of the proposed cycle (MERC) are shown in Fig. 3. The MERC system consists of a compressor (Cm), two condensers (Cn1,Cn2), a subcooler (Sc), an IHX (internal heat exchanger), a phase separator, a capillary tube (Ct), an evaporator (Ev) and an ejector (Eje). The phase separator is placed between Cn1 and Cn2 to obtain two steams with different refrigerant compositions utilizing the composition shift feature of the zeotropic mixture refrigerant during phase change. The subcooler is used to achieve subcooling for the saturated liquid from separator. In addition, the ejector is used to recover the expansion loss occurring in the throttling process from condenser 2 to evaporator and strengthen the recirculation of the refrigeration fluid coming from the evaporator by the entrainment effect of the ejector.

The detailed working principle of the MERC is described as follows: The initial composition mixture refrigerant (R290/R600a) leaves the compressor (state 2) and then enters the condenser 1, where it gets cooled by the secondary fluid (air) and obtains partial condensation. The two-phase fluid leaving condenser 1 and then is separated into two steams with different refrigerant compositions in the phase separator. The R600a enriched fluid enters the subcooler (state 4) and obtain further subcooling in subcooler (state 10), and then enters the nozzle as the primary fluid. The R290 enriched fluid (vapor phase) enters the condenser 2 (state 5) and rejects heat to the surroundings. Then, the leaving fluid of the condenser 2 enters the evaporator after a pressure drop in the capillary tube and achieves useful refrigeration effect in the vaporization process. The vapor fluid from evaporator (state 9) is entrained by the primary flow jetting from the ejector nozzle, and then the two streams mixes in the mixing chamber. The mixed flow leaves the ejector diffuser with a pressure rise (state 12) and enters the IHX to be superheated by dissipated heat of the fluid leaving condenser 2. Then the superheated flow (state 1) reenters the compressor. In this way, the whole cycle is completed.

Analysis from the cycle configuration, we could find that the modified cycle has some features as follows: First, utilizing the composition shift characteristic of the zeotropic mixture R290/R600a and placing a phase separator between the two condensers could achieve partial condensation. In this case, the evaporation pressure of the R290 enriched stream is higher, and the condensation pressure determined by the condenser 1 outlet temperature T_3 (evaluated as the condensation temperature T_c) and refrigerant quality x_3 ($0 < x_3 < 1$) is lower than those of the BTRC cycle at identical initial refrigerant composition, constant evaporator outlet temperature and condensation temperature. Second, an ejector is employed in this cycle, which not only recovers the expansion loss in the throttling process, but also utilizes its entrainment effect to strengthen the recirculation of the refrigeration fluid. And this is beneficial for the system performance improvement in practical application. According to conventional ejector expansion