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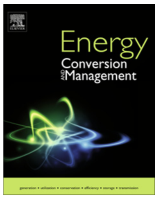

Energy and exergy analysis of a new ejector enhanced auto-cascade refrigeration cycle

Gang Yan, Jiaheng Chen, Jianlin Yu *

Department of Refrigeration & Cryogenic Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

A new ejector enhanced auto-cascade refrigeration cycle using R134a/R23 refrigerant mixture is proposed in this paper. In the new cycle, an ejector is used to recover part of the work that would otherwise be lost in the throttling processes. The performance comparison between the new cycle and a basic auto-cascade refrigeration cycle is carried out based on the first and second laws of thermodynamics. The simulation results show that both the coefficient of performance and exergy efficiency of the new cycle can be improved by 8.42–18.02% compared with those of the basic cycle at the same operation conditions as the ejector has achieved pressure lift ratios of 1.12–1.23. It is found that in the new cycle, the highest exergy destruction occurs in the compressor followed by the condenser, cascade condenser, expansion valve, ejector and evaporator. The effect of some main parameters on the cycle performance is further investigated. The results show that for the new cycle, the achieved performance improvement over the basic cycle is also dependent on the mixture composition and the vapor quality at the condenser outlet. The coefficient of performance improvement of the new cycle over the basic cycle degrades with increasing vapor quality. In addition, there exists an optimum mixture composition to obtain the maximum coefficient of performance for the new cycle when other operation conditions are given. The optimum mixture composition of both cycles may be fixed at about 0.5 under the given evaporating temperature.

1. Introduction

Zeotropic mixtures are blends of two or more working fluids that offer two features of the temperature glide and composition shift during phase change (evaporation and condensation) [1,2]. Utilizing the features of zeotropic mixtures, different kinds of zeotropic mixtures as alternative working fluids can be employed to achieve auto-cascade thermodynamic cycles for the refrigeration/heat pump and energy conversion applications. Early, the use of auto-cascade refrigeration cycles (ARCs) adopted with zeotropic mixtures obtained more practical applications since they can provide low and ultralow temperature refrigeration using a single compressor. Missimer [3] presented the brief history of the auto-refrigerating cascade systems and compared the steep glide zeotropes required for ARC system operation. Thus, some studies have been mainly focused on the ARCs for various low temperature refrigeration applications. There is a worldwide interest in the development of ARC refrigerators operating with zeotropic refrigerant mixtures.

Kim and Kim [4] investigated the performance of an autocascade refrigeration system using zeotropic refrigerant mixtures of R744/134a and R744/290. Test and simulation evaluated the system performance at various mass fractions of R744 and several operating conditions. Du et al. [5] carried out a study on the cycle characteristics of an ARC using the mixture R23/R134a, and found out the relations among the charging concentrations, temperatures of cooling water and matches of cycle flux between high and low boiling point components under the same evaporating pressure in the ARC system. Nayak and Venkatarathnam [6] presented an ARC system with optimum nitrogen-hydrocarbon and argon-hydrocarbon mixtures between 90 and 160 K, and revealed the exergy efficiency of a ARC system can be as high as that of a single stage system (without a phase separator) when optimum mixtures are used. Wang et al. [7] investigated the influence of the low pressure refrigerant mixing position in recuperators on the performance of an operating with a rectifying column, and provided a guide for the optimum design and application of the ARC refrigerator. Wang et al. [8] further simulated an ARC refrigerator operating with two vapor–liquid separators, indicated the main factors affecting coefficient of performance (COP) include the pressure ratio, the composition of mixed refrigerants, the main stream ratio

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* Corresponding author. Tel.: +86 29 82668738; fax: +86 29 82668725.
E-mail address: yujl@mail.xjtu.edu.cn (J. Yu).

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Nomenclature

COP	coefficient of performance
$\dot{E}x$	exergy rate of fluid (W)
$\dot{E}x_{\mathrm{d}}$	exergy destruction (W)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (k Pa)
q	vapor quality
Q_{c}	cooling capacity (W)
s	specific entropy (kJ kg^{-1} K^{-1})
t	Celsius temperature (°C)
T	Kelvin temperature (K)
w	velocity (m s^{-1})
W	compressor power (W)

Greeks symbol

η	efficiency
ξ_{ed}	exergy destruction percentage
μ	entrainment ratio

Subscripts

0	reference state
1–9	state points of refrigerant
c	cooling
com	compressor
ccon	cascade condenser
con	condenser
d	diffuser
e	evaporator
ej	ejector
eva	evaporator
ex	exergy
exp	expansion
h	heating
i	inlet
is	isentropic
m	mixing process
n	nozzle
o	outlet
p	primary flow
pj	pressure lift ratio of an ejector
s	secondary flow
t	total

and the pressure. Sivakumar and Somasundaram [9] conducted exergy and energy analysis of a three-stage ARC system using zeotropic mixture, and confirmed the use of the three component zeotropic mixture of R290/R23/R14 allow the ARC system operate at very low evaporating temperature. In addition, Zhao et al. [10] performed a thermodynamic analysis of an auto-cascade heat pump cycle for heating application in cold regions, and indicated the cycle using binary zeotropic refrigerant mixture R143a/R600 can improve the heating performance in cold climate. Bao and Zhao [11] presented exergy analysis and parameter study on a novel auto-cascade Rankine cycle, and showed the proposed cycle is thermodynamically better that conventional organic Rankine cycle.

In general, there is very little information available in the open literature on the ARCs. Over the past years, developments in the field of ARCs have been mainly limited to finding suitable zeotropic mixtures for providing refrigeration at low temperatures. Actually, further research also needs to be carried out to design more efficient ARC systems for improved energy efficiency, including modifying the refrigeration cycle, improving the performance of the heat exchangers and optimizing system components, etc. [12–14]. Typically, conventional ARCs usually use throttling devices to obtain refrigeration effects. The throttling processes generate more irreversibility for the cycle, and leading to the system performance to degrade. Thus, throttling devices are not ideally suitable to be configured in existing ARC systems. However, the use of ejectors as expansion devices may help reduce the expansion irreversibility and obtain work recovery in the ARCs. Currently, the applications of ejectors are of great interest in the refrigeration/heat pump cycles. Elbel [15] presented an overview of historical and present developments on how ejectors can be utilized to improve the performance of air-conditioning and refrigeration systems. Sarkar [16] given a review of the ejector enhanced vapor compression refrigeration and heat pump systems, while Sumeru et al. [17] presented a review on the two-phase ejector as an expansion device in the vapor compression refrigeration cycle. Lawrence and Elbel [18] compared three different two-phase ejector cycles by theoretical and practical method. Chen et al. [19] presented an ejector model to determine the optimum performance as well as obtaining the design area ratio of an ejector in a refrigeration system. Obviously, as a means of bring performance improvements, the use of ejectors in ARC systems could provide a solution to the development of more efficient systems. Bilir et al. [20] conducted an experimental study on the comparison of basic and ejector expander refrigeration systems using R134a refrigerant. The results show that the ejector can 39–42% energy recovery and improve the COP by 7.34–12.8%. Lawrence and Elbel [21] presented the experimental results of comparison between the two-phase ejector cycle and basic cycles with R134a and R1234yf refrigerants and shows maximum COP improvements of 12% with R1234yf and 8% with R134a.

This paper presents a new ejector enhanced auto-cascade refrigeration cycle (EARC) to promote its performance improvement. By using the ejector with a modified cycle system, the irreversibility in the cycle process can be reduced and resulting in better performance for the proposed EARC. In this paper, the performance characteristics of the EARC are theoretically analyzed based on thermodynamics methods, and its potential performance enhancement is evaluated by comparing to a basic ARC. The objective of the present study is to explore the possibility of using an ejector in the ARCs.

2. Cycle system description

Schematic diagram of the basic ARC system widely used in low temperature refrigeration fields is illustrated in Fig. 1. The basic ARC with zeotropic refrigerant mixture mainly consists of seven basic components, i.e. a compressor, a condenser, a phase separator, a cascade condenser, two expansion valves, and an evaporator. It can be seen that the system operation of ARC involves two expansion processes, which will certainly degrade its cycle performance owing to inducing significant energy and exergy loss. In this case, it could be a good solution to replace the expansion valve with an ejector, because the ejector can effectively recover the expansion work to lift the suction pressure of the compressor