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Advanced exergy analysis on a modified auto-cascade freezer cycle with an ejector

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ABSTRACT

This paper presents a study on a modified ejector enhanced auto-cascade freezer cycle with conventional thermodynamic and advanced exergy analysis methods. The energetic analysis shows that the modified cycle exhibits better performance than the conventional auto-cascade freezer cycle, and the system COP and volumetric refrigeration capacity could be improved by 19.93% and 28.42%. Furthermore, advanced exergy analysis is adopted to better evaluate the performance of the proposed cycle. The exergy destruction within a system component is split into endogenous/exogenous and unavoidable/avoidable parts in the advanced exergy analysis. The results show that the compressor with the largest avoidable endogenous exergy destruction has highest improvement priority, followed by the condenser, evaporator and ejector, which is different from the conclusion obtained from the conventional exergy analysis. The evaporator/condenser greatly affects the exogenous exergy destruction within the system components, and the compressor has large impact on the exergy destruction within the condenser. Improving the efficiencies of the compressor efficiency and the ejector could effectively reduce the corresponding avoidable endogenous exergy destruction. The exergy destruction within the evaporator almost entirely belongs to the endogenous part, and reducing the temperature difference at the evaporator is the main approach of reducing its exergy destruction.

1. Introduction

Currently, small-sized freezers for low temperature refrigeration attract much attention in the domestic and commercial applications, especially at the storage of frozen food and medical storage. In the past decades, multi-stage compression and cascade refrigeration cycle are generally used to obtain low and ultra temperature refrigeration below −50 °C. However, their systems are complex and the device investments are high, which limits the applications in small-sized freezers. Recently, the auto-cascade refrigeration cycles (ARCs) applied in low temperature refrigeration draws much interest, because its system structure is simpler and could realize the low temperature refrigeration with one stage compression using zeotropic refrigerant mixtures. The advantage of the ARC cycle was successfully used for gas liquation by Kleemenko in 1959 [1]. Thus, ARC cycles are more suitable to be applied in low temperature refrigeration such as commercial low temperature refrigerators, cryogenic coolers and natural gas liquefaction plants.

In the past decades, much work has been devoted on the auto-cascade refrigeration systems for different applications [2,3]. Kim and Kim [4] experimentally and theoretically explored the performance of an auto-cascade refrigeration system using zeotropic refrigerant mixtures of R744/134a and R744/290 at different operating parameters and refrigerants mass fraction. Xu et al. [5] investigated the variation of the refrigerant composition at different the expansion valve openings. Du et al. [6] experimentally studied the effect of the charging concentrations, cooling water temperatures and the matches of cycle flux between high and low boiling point components on the auto-cascade refrigeration cycle performance. Wang et al. [7] discussed the influence of the low pressure refrigerant mixing position in recuperators on the performance of an auto-cascade refrigerator equipped with a rectifying column. Sivakumar and Somasundaram [8] conducted the exergetic and performance analyses on a three stage auto-cascade refrigeration cycle with ternary zeotropic mixtures of R290/R23/R14 and R1270/R170/R14, and the mixture R290/R23/R14 with the mass fraction of 0.218/0.346/0.436 is suggested at the evaporating temperature of −97 °C. From the open literature on the auto-cascade refrigeration cycle, it could be concluded that much work has been focused on the cycle performance investigation and

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Nomenclature

COP	coefficient of performance
$\dot{E}$	exergy flow rate (W)
e	specific exergy (J kg^{-1})
h	specific enthalpy (J kg^{-1})
MAX	the largest element
$\dot{m}$	mass flow rate (kg s^{-1})
MIN	the minimum element
P	pressure (kPa)
Q	refrigeration capacity (W)
q_v	volumetric refrigeration capacity (J m^{-3})
r_P	pressure lift ratio of ejector
s	entropy (J kg^{-1} K^{-1})
T	temperature (°C)
ΔT	temperature difference (°C)
v	specific volume, (m^3 kg^{-1})
x	refrigerant quality
W	compressor power (W)

Greek symbols

ϕ	exergy destruction ratio
ε	component exergy efficiency
η_{Ex}	system exergy efficiency
μ	entrainment ratio
λ	mass flow allocation ratio

Superscripts

AV	avoidable
EN	endogenous
EX	exogenous
UN	unavodiable
T	thermal
M	mechanical
PH	physical

Subscripts

CM	compressor
CON	condenser
D	exergy destruction
d	diffsuer
EJE	ejector
EXP	expansion valve
EV	evaporator
E/C	evaporator/condenser
F	exergy fuel
L	exergy loss
n	nozzle
P	exergy product
p	primary flow
s	secondary flow
tot	total
1–16	state point
0	reference condition

refrigerant selecting to gain better performance and reduce the impact of refrigerants on environment. Actually, further research needs to be carried out on the system modification [9,10], component optimization design [11], etc, to improve the energy utilizing efficiency of auto-cascade refrigerators.

The auto-cascade refrigeration cycle with binary refrigerants mixture is the simplest auto-cascade cycle, so it is more acceptable and practical to be applied in small-sized freezer at the refrigeration temperature from −50 °C to −60 °C. However, the low temperature auto-cascade refrigeration cycle generally exhibits lower system performance due to the large throttling losses generated in expansion valves. Therefore, recovering the throttling loss in expansion valves is an efficient method of improving the system performances of auto-cascade refrigeration cycles. Ejector is a proposed device to replace the conventional expansion valve and recovery expansion work, which could effectively enhance the performances of a system with large throttling loss [12,13]. And ejector technique is widely applied in to various refrigeration systems including different auto-cascade refrigeration cycles [9,14,15]. It could be concluded that a remarkable improvement could be achieved with the energy saving effect of an ejector. Therefore, significant performance improvement of the auto-cascade refrigeration cycle could be obtained with proper modification using an ejector.

This paper presents a modified ejector enhanced auto-cascade refrigeration cycle (MEARC) to enhance the system performances. To show the advantages of the modified cycle, the energetic performance comparison is carried out among the MEARC, the conventional auto-cascade refrigeration cycle (CARC) and another ejector enhanced auto-cascade refrigeration cycle (EARC) [14]. In addition, a recently developed technique, i.e., advanced exergy analysis method, is applied as a supplementary method of the conventional exergy analysis to analyze the system exergetic performance. This method could quantitatively assess the mutual interdependencies among the system components and determine the potential of improving the thermodynamic performance. And thus it is recognized as a supplementary method of the conventional exergy analysis [16]. Recently, more and more researchers use advanced exergy analysis method to investigate the irreversibility generation in various energy systems, such as power plants [17–19], natural gas liquefaction systems [20,21] and building heating systems [22,23]. Meanwhile, similar theoretical research has been carried out on different refrigeration cycles including basic vapor compression refrigeration cycles [24,25], ejector refrigeration cycles [26] and absorption refrigeration systems [27], etc. However, little research has been performed on the auto-cascade refrigeration cycles with the advanced exergy analysis. In this study, a theoretical investigation on the MEARC cycle is performed with the advanced exergy analysis method. This study aims to explore the real system improvement potential and the relationships among the components, and get possible approaches of improving the system energy utilizing efficiency.

2. System description

The cycle layouts and pressure-enthalpy diagrams the conventional and ejector enhanced auto-cascade refrigeration cycles, i.e., CARC and EARC cycles, are shown in Figs. 1 and 2, respectively. It could be found that the CARC cycle consists of a compressor (CM), a condenser (CON), a phase separator (PS), an evaporator (EV), an evaporator/condenser (E/C) and two expansion valves (EXP). The phase separator is used to obtain two mixtures with different refrigerant compositions (i.e., mixture-2 and mixture-3), since the composition of zeotropic mixture refrigerant shifts evidently in the phase change process. An evaporator/condenser is used to liquefy the vapor stream from the separator (mixture-3) with low temperature two-phase flow after the expansion valve-1 (mixture-2). Generally, it is believed that this cycle yields low system