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Conventional and advanced exergy analysis of an ejector refrigeration system

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HIGHLIGHTS

- Conventional and advance exergy analysis are applied.
- Splitting the exergy destructions is well illustrated.
- Ejector should be firstly improved, followed by condenser then generator.
- Condenser has the largest influence compared to generator and evaporator.
- The system is largely improved by improving the ejector.

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ABSTRACT

This paper presents a comprehensive investigation of an ejector refrigeration system using conventional and advanced exergy analysis. Splitting the exergy destruction within each system component into endogenous/exogenous and avoidable/unavoidable parts provides additional useful information and improves the quality of the exergy analysis. Detailed calculations of the exergy destruction parts are schematically illustrated. Conventional exergy analysis indicates that about half of the total exergy destruction is caused by the ejector and about one quarter occurs in the generator. The advanced exergy analysis reflects the strong interactions between system components. The ejector has the highest priority to be improved, followed by the condenser and then the generator. The temperature difference in the condenser has the largest influence on the exergy destruction compared to that in the generator and the evaporator, and the ejector efficiencies are also very crucial for the exergy destruction. The system performance can be largely enhanced through improvements of the ejector and the condenser as well as the generator.

1. Introduction

The vapor compression refrigeration systems face a number of difficult challenges over the coming decade, the most prominent being a possible ban of fluorocarbon refrigerants, increasing energy prices, and growing environmental concerns. A possible alternative is to turn to renewable energy and seek possibilities of utilizing waste heat. An ejector refrigeration system offers a promising option to utilize solar energy with an interesting feature for air-conditioning applications since solar radiation is generally in phase with cooling demands. Another possibility is to harvest low-grade waste heat from industrial processes to produce cooling so that the problems related to CO_2 emission and costs can be reduced. The ejector refrigeration system is characterized by a simple structure, a long lifespan, low capital cost and little maintenance. Moreover, various environmentally-friendly refrigerants can be used, making such a system very attractive in this energy-conscious era. However, the system COP is relatively low, which limits its wide spread implementation. Researchers have made continuous efforts to increase the knowledge of ejector behavior and improve the system performance by using different methods.

Various mathematical models have been proposed to formulate ejector working processes with assumptions and simplifications. The ejector theory proposed by Keenan et al. [1] in 1950 was considered as the basis of many other ejector models and fundaments of ejector design. Huang et al. [2] predicted the ejector performance at critical condition, and verified with experimental data. Zhu et al. [3] developed a two-dimensional ejector model by introducing a “shock circle” at the entrance of the constant area section. Computational Fluid Dynamics (CFD) enables the possibilities to obtain three-dimensional and local flow features in the ejector [4].

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Nomenclature

Symbols

COP	coefficient of performance
$\dot{E}$	exergy (kW)
e	specific exergy (kJ kg^{-1})
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (kPa)
Q	heat load (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C)
ΔT	temperature difference (°C)
W	work (kW)
y	exergy destruction ratio

Greek symbols

μ	entrainment ratio
ε	exergetic efficiency
η	efficiency

Superscripts

AV	avoidable
CH	chemical
EN	endogenous
EX	exogenous
KN	kinetic
PH	physical
PT	potential
UN	unavoidable
T	thermal
M	mechanical

Subscripts

CO	condenser
d	diffuser
D	destruction
EV	evaporator
ei	reversible ejector outlet
EJ	ejector
F	fuel
GE	generator
i	ideal
j	exergy carrier positions
k	the k-th component
L	loss
m	mixing
n	nozzle
P	product
PU	pump
TV	throttling valve
tot	overall
0	reference condition
1–12	locations in the system
$e1$–$e4$	locations inside the ejector

The refrigerant is directly related to the system performance and ejector design. Chen et al. [5] and Kasperski and Gil [6] compared different refrigerants and their feasibility in ejector refrigeration systems. To improve the system performance and make it more economically sound, attention has been paid to the optimization of ejector geometries. The variable-geometry ejector has been considered as a promising solution to widen the ejector operating ranges [7]. This is realized by placing a spindle at the ejector nozzle throat [8], or by using a moving nozzle [9]. Most of the ejector modeling is from the perspective of the first law of thermodynamics.

Using the second law of thermodynamics, the exergy analysis, is useful to identify the location, magnitude and sources of exergy destruction. Pridasawas and Lundqvist [10] performed an exergy analysis on a solar-driven ejector refrigeration system working with butane and found that the most significant exergy destruction for the ejector refrigeration cycle occurred in the ejector. This result was later confirmed by Alexis [11] using water as the working fluid. Dahmani et al. [12] claimed more than half of the total exergy destruction within the ejector refrigeration system working with R134a was in the ejector. In the ejector enhanced refrigeration systems, the exergy analysis has also been widely used to identify the improvement by adding the ejector. It was found that the ejector could improve the COP of a vapor compression refrigeration system with R134a by 16% and decrease its total exergy destruction by 24% [13]. In CO_2 transcritical refrigeration system, the ejector was able to reduce the total exergy destruction by 23% compared to the standard cycle [14]. This reduction was proven to be more significant in the two stage CO_2 system [15]. However, the mentioned exergy method, termed conventional exergy analysis, has its limits [16] and could lead to some misinterpretations [17].

In the ejector refrigeration system, the ejector operating parameters, which depend on the ejector itself and other components, are closely related and interact with each other [18]. But these interconnections have never been analyzed quantitatively. The conventional exergy analysis cannot assess the mutual interdependencies among the system components [16]. A recent developed technique, the advanced exergy analysis, makes this possible by splitting the exergy destruction in each component into endogenous and exogenous parts. An additional splitting of the exergy destruction into avoidable and unavoidable parts provides a realistic evaluation of the potential for improvement [16]. The advanced exergy analysis has been extensively applied in different refrigeration systems, like vapor compression refrigeration systems [17,19], absorption refrigeration systems [20,21] as well as heat pump [22]. The advanced exergy analysis provides additional and useful information that cannot be obtained through the conventional exergy analysis.

To the authors' best knowledge, no investigations on applying the advanced exergy analysis to ejector refrigeration systems have been reported. The objective of this paper is therefore to pioneer the use of advanced exergy analysis in the ejector refrigeration system, and to reveal more detailed information about relationships among the components and the real improvement potential of the system. Splitting the exergy destruction within each system component is schematically described and interpreted. The key parameters are parametrically studied, and strategies of improving the system performance are presented. The results are expected to help in exploring working characteristics of the ejector refrigeration system that never reported before and make the system more efficient.

2. System description and assumptions

An ejector refrigeration system consists of three heat exchangers (a generator, a condenser and an evaporator), an ejector, a pump and a throttling valve, as well as three brine side fluid paths