Energy Conversion and Management 90 (2015) 184–194

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Energetic and exergetic comparison of basic and ejector expander refrigeration systems operating under the same external conditions and cooling capacities

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ARTICLE INFO

Article history:
Received 7 August 2014
Accepted 12 November 2014
Available online 27 November 2014

Keywords:
Refrigeration
Ejector
Throttling loss
COP
Exergy efficiency
Exergy destruction

ABSTRACT

An experimental study was conducted on vapor compression refrigerators using R134a refrigerant for the purpose of achieving energy recovery and decreasing the effects of irreversibility. An ejector was used as an expander instead of an expansion valve. The coefficient of performance of the ejector refrigeration system and the amount of irreversibility and efficiency of each of its components were determined and compared with those of a basic vapor compression refrigeration system of the same cooling capacity under the same external conditions. It was found that the ejector expander system exhibited a lower total irreversibility in comparison with the basic system. When the ejector was used as the expander in the refrigeration system, the coefficient of performance was higher than in the basic system by 7.34–12.87%, while the exergy efficiency values were 6.6–11.24% higher than in the basic system.
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1. Introduction

The progressive increase in energy consumption and decrease in natural energy resources have necessitated a more efficient use of energy. One area of research for improving energy efficiency is to reduce the throttling losses in the expansion valve of a basic vapor-compression refrigeration cycle. Recent studies on the topic have investigated the use of a simple ejector with no moving parts, instead of an expansion valve, to ascertain whether this can improve the coefficient of performance (COP) of a refrigeration system.

An ejector can be used either as a thermal compressor in the heat-driven cycle [1–8], or as an expander in the compressor-based cycle, as described in this paper. However, using an ejector for the expander is relatively uncommon in refrigeration systems [9]. There are several subcritical and CO_2-based transcritical studies [10–16] in the literature that have investigated the use of ejectors instead of expansion valves. The idea of using ejectors instead of expansion valves in subcritical cycles was first put forward by Gay in 1931 [17]. Kornhauser [18] theoretically determined that the use of an ejector in a conventional refrigeration system using R-12 refrigerant would improve the COP by 21%. However, an improvement in the COP of approximately 2.3% to 3.1% was found experimentally [19].

In a study by Nehdi et al. [20] it was theoretically found that the ejector's geometric parameters have a considerable influence on the system performance. Bilir and Ersoy [21] found theoretically that a basic refrigeration system using R134a refrigerant could achieve a COP increase of 22.3% if an ejector were used. Furthermore, in this study, it was determined that the ejector system exhibits a higher COP than the basic system, even at off-design operating conditions. Ersoy and Bilir [22] investigated theoretically the exergy efficiency, irreversibility, and effects of the ejector elements' efficiencies on the COP of an ejector refrigeration system. They found that as the efficiencies of the ejector elements increase, the system performance increases and the ejector area ratio decreases.

Pottker et al. [23] conducted an experimental study on an ejector-expander refrigeration system using R410A refrigerant, and found that the system COP was 8.2% better when compared with the basic refrigeration system of the same cooling capacity and under the same operating conditions. In addition, they determined that as the condenser temperature increases, the improvement in COP keeps increasing. Hu et al. [24] compared experimentally an ejector-expander and basic refrigeration system using R410A refrigerant, and found an improvement in energy effectiveness of 9.1% over the basic system.

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http://dx.doi.org/10.1016/j.enconman.2014.11.023
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Nomenclature

C_p	heat capacity at constant pressure (kJ kg^{-1} K^{-1})
$\dot{E}x$	exergy destruction rate (kW)
f	frequency (Hz)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (kPa)
$\dot{Q}$	cooling capacity rate (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C or K)
$\dot{V}$	volumetric flow rate (m^3 h^{-1})
$\dot{W}$	power or work rate (kW)

Greek letters

ρ	density (kg m^{-3})
η	efficiency (–)
x	vapor quality (–)
ω	mass flow ratio (–)
Ψ	exergy efficiency (–)

Subscripts and abbreviations

a	*sound speed*
av	*average*
b	brine
c	condenser
COP	coefficient of performance
cp	compressor
des	destruction
dif	diffuser
e	evaporator
EES	Engineering Equation Solver
EERC	ejector-expander refrigeration cycle
ej	ejector
exp	expansion valve
i	inlet
is	isentropic
m	mixing chamber
max	maximum
ne	primer nozzle exit
o	out
ov	overall
p	primary nozzle
rpm	revolutions per minute
s	suction nozzle
sep	separator
tot	total
SC	subcooling
SH	superheating
sys	system
t	cross section of primary nozzle throat
v	vapor
VCRC	vapor-compression refrigeration cycle, basic cycle
w	water
wr	work recovery
0	reference environment

The fact that separation efficiency of an ejector expander refrigeration system affects the system performance was stipulated in a study by Reddick et al. [25]. The liquid–vapor separating efficiencies of the separator are defined in the following manner: The liquid separation efficiency is the ratio of the mass flow rate of liquid at the separator liquid port to the mass flow rate of liquid into the separator. Similarly, the vapor separation efficiency is defined as the ratio of the mass flow rate of vapor at the separator vapor port to the mass flow rate of vapor into the separator [26]. In order to maintain a complete vapor phase of the refrigerant flowing from the separator to the compressor, three electric heaters were used in the proximity of the compressor inlet [25]. It was determined that when the total power of the heaters is added to the evaporator cooling capacity, the COP of the ejector system surpasses that of the basic system by 11%. However if the power of the heaters is not taken into account during the COP calculations, then the COP of the ejector system becomes lower than that of the basic system, for R134a refrigerant. It was found that if the efficiency of the separator becomes lower than 85% (15% inefficiency) then there is no benefit to using an ejector, as it will not yield any improvement [27]. A separator inefficiency of 15% means that the separator was able to convey 85% of the vapor mass and liquid mass from the saturated mixture in the ejector to the compressor and evaporator, respectively. In another experimental study with R134a refrigerant, the separator in a refrigeration system was replaced by an ejector-expander system with two evaporators, and it was found that this new system had a COP 10% higher than a basic system with two evaporators operating under the same conditions [28]. Zhou et al. [29] theoretically investigated a novel dual-nozzle ejector-enhanced refrigeration cycle for dual-evaporator household refrigerator–freezers. They found that the COP was 10.5–30.8% higher than the basic refrigeration cycle with two evaporators, for the same cooling capacity. A new refrigeration system with two evaporators using an ejector as a throttling valve was also investigated [30]. They found that at the same cooling capacity, the COP of the new system was higher than that of the classic cycle with two evaporators.

There are fewer experimental studies that have investigated the use of ejectors instead of expansion valves in a basic R134a vapor-compression refrigeration system. The United Nation Environment Programme (UNEP) promotes the R134a refrigerant as the high side fluid in the R134a/CO_2 cascade refrigeration systems as a high-security low-GWP solution for centralized commercial refrigeration, especially for supermarkets [31]. Harrel and Kornhauser conducted an experimental study on an R134a ejector-expander refrigeration system, and with this system they achieved an improved COP in the range of 3.9–7.6% [17]. This low level of improvement is attributed to the dependence on single-phase flow ejector design, and the lack of two-phase ejector flow details. In several studies spearheaded by Wongwises, experimental analyses were carried out on ejector-expander refrigeration systems [32–34]. In all of these studies, the evaporator used was of the wet type, and the refrigerant on the low-pressure side was partly recirculating. However, when an ejector was used in these studies, the amount of improvement in the COP was not specified. Reddick [35] also mentioned that no remarkable improvement could be spotted in the studies carried out by Wongwises' team. Lawrence and Elbel [28] analyzed refrigeration cycles that use no separators and those that make use of ejectors with two evaporators, and experimentally compared them with the basic refrigeration cycles having two evaporators. They found that the second principle efficiency of the ejector expander system with two evaporators and with no separator was 8.5% higher than that of the basic system with two evaporators. Sumeru et al. [36] conducted an experimental study on split-type air conditioners, where instead of using the basic ejector system (two exits from the separator), the researchers used a modified ejector system (single exit from the separator), and concluded that with the modified system the COP value would

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