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Evaluation of the ejector refrigeration system with environmentally friendly working fluids from energy, conventional exergy and advanced exergy perspectives

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ABSTRACT

This paper presents the evaluation of the ejector refrigeration system from three levels: energy analysis, conventional exergy analysis and advanced exergy analysis, in light of introducing the thermal conductance and the objective function, the exergy efficiencies, the exergetic rehabilitation ratio and the exergetic improvement potential ratio, respectively. Five environmentally friendly working fluids, namely R600, R600a, R601a, R1233zd(E) and R1234ze(E), are used to compare their performance and working characteristics in the system. At the normal condition, it is found that these candidates have different orders of highest performance by different analysis, but agree that the ejector has the highest priority of improvement. The parametric study shows that these candidates have the same optimum pinch temperature differences in the condenser (7 °C and 3 °C) and in the evaporator (3 °C and 2 °C) to minimize the thermal conductance and the objective function, while they are different in the generator. The ejector efficiencies have considerable influence on the system performance, and a 0.1 increase in ejector efficiency could lead to the increase of system exergy efficiency from 1.38% to 10.33%. The pump efficiency has insignificant influence the system performance, but a 0.1 increase in the pump efficiency results in a 7.37% decrease in exergetic improvement potential ratio of the pump. By comprehensive comparisons, R1233zd(E) has generally higher system performance than the other four candidates, it is therefore recommended as the good working fluid for the ejector refrigeration system.

1. Introduction

Refrigeration and air-conditioning units as well as heat pumps are dominated by vapor compression refrigeration systems and consume about 17% electricity world-widely [1]. The electrical peak load problems during summer and environmental issues have consequently become more serious than ever before. This raises voices for seeking approaches of utilizing renewable energy and low-grade heat to produce cooling. The ejector refrigeration system, abbreviated as ERS, is driven by the thermal energy and seems to be a good alternative. It has merits of simple construction, low cost, long lifetime, flexible capacity, no-chemical corrosion and chemical reaction over the sorption refrigeration systems. Moreover, its capability of applying various environmentally-benign refrigerants makes such system particularly attractive in this energy-environment-conscious era. However, it has relatively low *COP*, which greatly limits its application in commercial and wide scales. A number of investigations have been conducted to get a better understanding of ejector characteristics and to improve the system performance. Zhu et al. [2] visualized the flow phenomena inside the ejector. Chen et.al [3] proposed an ejector model to predict the optimum performance. Chen et al. [4] developed a 1D model to evaluate the ejector performance at critical and sub-critical operation.

The working fluid is essential since a proper working fluid can not only benefits the ejector and system performance, but also bring less system failures and environmental issues. As new refrigerants are merged and developed, they have been extensively examined and compared in the ERS. Table 1 summarizes the typical researches [4–13]. It is obvious that (1) different working fluid performs quite differently and the system *COP* is generally below 0.9; (2) there are no agreements reached in terms of which working fluid has the best performance. This is due to the different operating conditions; (3) many refrigerants are used, including

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Nomenclature

Symbols*COP*

	coefficient of performance
$\dot{E}$	exergy (kW)
EIP	exergetic improvement potential ratio
ERR	exergetic rehabilitation ratio
F	objective function
h	specific enthalpy (kJ/kg)
LMTD	logarithmic mean temperature difference (°C)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
Q	heat load (kW)
s	specific entropy (kJ/kg·K)
T	temperature (°C)
ΔT	temperature difference (°C)
UA	thermal conductance (kW/K)
W	work (kW)

Greek symbols

μ	entrainment ratio
ε	exergetic efficiency
η	efficiency
$\Delta\eta$	efficiency difference

Subscripts

CO	condenser
d	diffuser
D	destruction
EV	evaporator
EJ	ejector
F	fuel
GE	generator
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

Table 1
Summary of the working fluids compared in the ERS.

Reference	Selected working fluids	Operating conditions			*COP*	Recommendation
		T_g (°C)	T_c (°C)	T_e (°C)		
Chen et al. [4]	R123, R124, R134a, R141b, R142b, R152a, R290, R600, R600a, R717	60–100	16–40	5–15	0.15–1.65	R290
Sun [5]	R11, R12, R113, R21, R123, R142b, R134a, R152a, RC318, R500, R718	80, 90	35, 25	5, −5	0.02–0.50	R152a
Selvaraju and Mani [6]	R134a, R152a, R290, R600a, R717	62–87	24–36	5	0.05–0.40	134a
Roman and Hernandez [7]	R123, R134a, R152a, R290, R600, R600a	70–100	25–35	5–15	0.27–0.84	R290
Chen et al. [8]	R134a, R152a, R290, R430A, R600, R245fa, R600a, R1234ze(E), R436B	75–125	27–43	0–16	0.05–0.70	R245fa, R600
Shestopalov et al. [9]	R123, R141b, R142b, R236fa, R245ca, R245fa, R600, R600a	95	32	12	0.41–0.51	R141b
Besagni et al. [10]	R134a, R141b, R152a, R290, R600, R600a, R601, R601a	60–180	30–50	5–15	0.03–0.40	R152a
Milazzo and Rocchetti [11]	R152a, R245fa, R236ea, R600a, R1233zd(E), R1234ze(E), R134a, R1234yf, R365mfc, R718	80–180	25–40	5,10	0.02–0.60	R1233zd(E)
Saleh [12]	R134a, R227ea, R245ca, R245fa, R236ea, R236fa, R600, R600a	60–110	25–45	−5–15	0.06–0.75	R245ca
Kasperski and Gil [13]	R290, R600, R600a, R601, R601a, R602, R602a, R603, R604	60–200	40	10	0.05–0.32	*

* The best *COP* were obtained by R600a when T_g is at 65–115 °C, R600 at 115–130 °C, R601a at 130–160 °C, R601 at 160–175 °C, and R602a at over 175 °C.

chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs) and hydrofluorocarbon (HFCs) and so on. However, some of them have already been prohibited or will phase out in a short future. For example, CFCs and HCFCs have been banned by Montreal protocol because of the damage of the stratospheric ozone layer known as ODP (Ozone Depletion Potential). Kyoto protocol was later proposed to control greenhouse gases including HFCs due to their global warming impacts. In 2006, EU came out with the Directive that set the limit on GWP (Global Warming Potential) value of refrigerant to be used in mobile air conditioning (MAC) [14]. More recently, EU Regulation No. 517/2014 (known as F-Gas) imposed a drastic phase-down of HFCs starting from 2015 and the reduction of greenhouse gases emissions by 2030 [15]. Hence the working fluid with zero ODP and low GWP is regulated and promoted. For this reason, the environmentally-friendly working fluids are being popularly considered in the ERS in up-to-date literature. It has to point out that the studies listed in Table 1 are based on the first law of thermodynamics, called as energy analysis, to comparably investigate the feasibility of working fluids in the ERS with respect to the energy quantity. However, this method is insufficient to locate the irreversibility within the components.

The exergy analysis, based on the second law of thermodynamics, takes both quantity and quality of energy into consideration, and is a powerful tool to identify the location, magnitude and source of the exergy destruction. It has been widely applied to the ERS. Pridasawas and Lundqvist [16] performed an exergy analysis on a solar-driven ERS with R600 and found that the ejector had the largest exergy destruction, followed by the generator, the condenser, the pump, the evaporator and the throttling valve. Similar result was also found by Dahmani et al. [17] using R134a and Chen et al. [18] using R245fa as the working fluid, except that the pump had the least exergy destruction. Alexis [19] concluded that in an R718 ERS the most significant exergy destruction occurred in the ejector, then in the condenser, the generator, the evaporator and the throttling valve. Sadeghi et al. [20] pointed out that the magnitude of the exergy destruction in descending order was the generator, the ejector, the condenser, the evaporator, the pump and the throttling valve when using R141b in an ERS. The disagreements are because, on the one hand, the different operating conditions are employed, on the other hand, the thermodynamic properties of the working fluid take great responsibility of remarkably impacting the ERS performance and the ejector behavior.