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Exergetic and economic analyses of a novel modified solar-heat-powered ejection-compression refrigeration cycle comparing with conventional cycle

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ABSTRACT

In this paper, a novel modified ejection-compression refrigeration cycle is studied and compared with conventional ejection-compression refrigeration cycle based on exergetic and economic analyses. The novel cycle is expected to improve the low practicability of conventional ejection-compression cycle with better thermal efficiency, smaller solar collector and more excellent economic performance. Energy performance is simply evaluated based on thermal efficiency and global coefficient of performance. The results show the novel cycle is better in both the two indicators, which confirmed that it needs much less solar heat and smaller collector, and has better practicability. With the above data, exergy analysis is performed, showing the total exergy destruction of the novel cycle is 23.97 kW less than a conventional cycle and exergy efficiency of the novel cycle is always higher than the conventional cycle in the studied range. Economic analyses taking into consideration the impact of carbon dioxide emission are finished under base case. The results reveal the novel cycle has a total cost rate 24.4% lower and a solar collector 89.5% smaller than those of a conventional cycle. The economic advantage of the novel cycle will remain, even both electricity price and carbon dioxide penalty cost increase to 3.1 times of the current price. These improvements in energy and economy indicate the novel cycle has an excellent application potential.

1. Introduction

Nowadays global warming and energy saving have become one of the most critical topics [1]. Increasing consumption of fossil fuels is the main cause of the problems [2], therefore the utilization of low-grade heat energy, such as solar energy may be possible to solve the problems [3]. Since vapor compression refrigeration and cooling systems consume huge quantity of high-grade energy [4], the refrigeration technology based on solar heat has evolved into a hot topic [5], and ejector refrigeration cycle (ERC) is a typical example with advantages like simple structure, less maintenance requirements and long lifetime. However, there are also some shortcomings that hamper the extensive use of ERC [6], such as low efficiency with low evaporation temperature and poor stability due to powered by solar heat [7]. To solve these disadvantages to some degree, ejection-compression refrigeration cycle [8], which combines an ejector refrigeration cycle to a vapor-compression refrigeration cycle [9], is investigated in many studies as follows.

In 1990, a compressor enhanced ejector system with the compounding of mechanical and thermal energies was proposed by Sokolov et al. [10]. The overall performance of this hybrid system has been significantly improved compared with the traditional ejector refrigeration system. The hybrid system obtained a COP of approximately 6.8, which delivered 3 kW of cooling capacity, when the evaporation temperature and the condensation temperature were assumed 282.15 K and 326.15 K respectively. Subsequently, the numerical evaluation and comparative analysis show that the ejector-assisted compression refrigeration system [11] and booster-assisted ejector refrigeration system [12] have better system performance than simple ERC. An ejector enhanced vapor compression refrigeration cycle with better cycle performance is proposed [13]. In a word, they carried out further investigation on the performance enhancement of the ERC and acquired the higher COP than the simple ejector cycle. Sun [14] applied a new way for harnessing solar energy, which was described as a solar-powered combined ejector-vapor compression cycle. Since the author only considered electrical energy rather than heat energy, the high COP value between 4 and 6.8 in the experimental results was discovered. As the two sub-cycles can use different refrigerant, an in-depth study from

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Nomenclature

A	heat transfer area (m^2)
A_{sol}	solar collector area (m^2)
C_{ele}	electricity price (US$/kWh)
C_{CO_2}	penalty cost for CO_2 emission (US$/kg)
CECR	conventional ejection-compression refrigeration cycle
COP_{th}	thermal efficiency
COP_g	global coefficient of performance
CRF	capital recovery factor
ex	specific exergy (kJ/kg)
Ex	exergy rate (kW)
Ex_D	exergy destruction rate (kW)
h	enthalpy (kJ/kg)
H	heat transfer coefficient (W/(m^2 K))
I_{sol}	solar intensity (kW/m^2)
$\dot{m}$	mass flow rate (kg/s)
m_{CO_2}	CO_2 emission mass (kg)
MECR	modified ejection-compression refrigeration cycle
n	system life time (year)
p	pressure (Pa)
Q	heat transfer rate (W)
$\dot{Q}_m$	heat load of evaporator-condenser or evaporator-sub-cooler (W)
t_{op}	annual operating hours (h)
T	temperature (K)
ΔT	temperature difference (K)
U	overall heat transfer coefficient (W/(m^2 K)) or entrainment ratio
v	specific volume (m^3/kg)
w	mass fraction of LiBr
$\dot{W}$	compressor power (W)
x	quality
Z	investment cost (US$)
$\dot{Z}$	cost rate (US$/year)
η	efficiency
η_{orc}	thermal efficiency of organic Rankine cycle
η_{sol}	efficiency of solar collector
λ	emission conversion factor
φ	maintenance factor

Subscript

amb	ambient
c	condensing
cold	cold thermal reservoir
com	compressor
dead	dead state for exergy
e	evaporating
ele	electricity
env	environment
ex	exergy
g	generation
hot	hot thermal reservoir
i	inlet or inner side
inv + main	investment and maintenance
in	input
is	isentropic
jct	ejector
k	component
lm	logarithmic mean
m	intermediate
o	outlet or outer side
op	operational
out	output
pump	pump
sc	subcooling
sh	superheating
1–13	state point

the perspective of selecting different working fluid was conducted [15]. For example, Petrenko et al. [16] studied the cascade refrigeration cycle, which is the combination of a mechanical compression refrigeration cycle with CO_2 as working substance and a waste heat powered ejector cooling system using butane as working fluid. The consequences revealed that the COP of the system increased from 1.3 to 6.4 with the variable evaporation temperature from 233.15 to 273.15 K.

Nevertheless, the use of solar energy often leads to a significant economic cost as a huge collector area is required for small cooling capacity. Colle et al. [17] described the economic analysis of a hybrid ejector-vapor compression refrigeration cycle powered by solar energy, and on the basis of this, they applied the f-$\overline{\varphi}$-chart method to optimize the collector area. But, the results show that the cooling capacity of 10.55 kW still needs 102 m^2 of collector area. Chesi et al. [18] also analyzed the complex cycle of using solar-assisted ejector machine to increase the efficiency of traditional vapor compression machine, and provided 20 m^2 of solar collector area, only the cooling capacity of 3 kW was obtained. An idea of coupling the solar powered ejector cycle with the vapor compression refrigeration cycle was presented by Chesi et al. [19]. The study demonstrated that the coupled ejection-compression refrigeration system providing 15 kW cooling capacity can increase yearly COP from 5.05 to 5.75, with a solar collector of 100 m^2, which is huge comparing to the system cooling capacity. Arbel et al. [20] studied the enhanced ejector refrigeration cycle, which consumed a low-grade heat of 6.74 kW provided by a 23.5 m^2 solar collector plate to achieve a cooling capacity of 3.5 kW. However, the solar energy conversion rate is only 41% and the problem of relatively large solar collector and investment cost still exists. The optimization of a thermally driven ejection-compression cooling cycle assisted by solar energy was described by Vidal et al. [21], which analyzed both the intercooler temperature and the area of flat plate solar collector. To obtain a cooling capacity of 10.5 kW, the optimized system consumed solar energy 12.8 kW provided by 105 m^2 solar collector plate, and a COP of the hybrid cycle equal to 0.89.

On the basis of the above literature survey, the utilization of conventional ejector-compression refrigeration cycle (CECR) with low-grade heat energy can augment energy saving and system performance obviously, but there is a challenge to the huge area of solar collector of CECR (compared with cooling area), which may lead to extremely high price and lack of installation area in multistory buildings. As the practicability is not very good, the energy-saving effect of CECR is limited, although it has a high COP. A novel modified ejector-compression refrigeration cycle (MECR) with different cycle structure [22] may help solve this problem. In MECR a vapor-liquid separator is installed between two throttling valves to assign the vapor refrigerant to enter the ejector at intermediate pressure. Therefore, MECR can be expected to improve heat efficiency, lower solar heat consumption and reduce collector area.

Both MECR and CECR can save electric energy compared with vapor compression refrigeration cycle. However, since MECR focuses on the decrease of heat consumption, it may not be advance in reducing electricity consumption, compared with CECR. Exergetic comparison taking into account both heat and electricity exergy is needed to understand the energy performance of the two cycles. MECR also aims at reducing collector cost and improving cycle practicability, so an economic comparison is necessary. Therefore, based on exergetic and