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Research Paper

Performance evaluation and energy-saving potential comparison of a heat-powered novel compression-enhanced ejector refrigeration cycle with an economizer

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HIGHLIGHTS

- A novel compression-enhanced low-grade-heat powered ejector cycle with economizer is proposed.
- The new cycle is compared with conventional cycle, revealing excellent performance.
- The new cycle can increase COP by 22.8% and reduce electric consumption by 18.4%.
- Optimized operating parameters for both cycles are obtained based on COP and COP_g.

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ABSTRACT

In this paper, a novel compression-enhanced ejector refrigeration cycle with an economizer (CERCE) is proposed for the first time to further reduce the electric consumption of conventional compression-ejection refrigeration cycle (CERC). A model is developed and validated to study the cycle. The proposed cycle (CERCE) is analyzed and compared with conventional compression-ejection cycle (CERC) based on COP and global COP (COP_g). In the studied temperature ranges, the COP and COP_g of CERCE are always higher than those of CERC. The maximum COP and COP_g for CERCE (6.30, 2.40) are 21.95% and 5.48% higher than those of CERC (5.17, 2.27) respectively, which demonstrates the excellent energy-saving potential of CERCE and proves that CERCE can improve energy performance. Analysis shows that the improvement is mainly caused by the decrease in compressor mass flow rate, while the decrease in secondary flow rate and the increase in entrainment ratio also have positive but very slight effects. Based on COP, optimized operating parameters for both cycles are obtained as $T_g = 75$ °C and $T_m = 7$ °C. Based on COP_g, the optimized operating parameters are $T_g = 55$ °C and $T_m = 26$ °C. These results provide direction for experimental study and practical operation.

1. Introduction

With the development of the human society, the greater energy consumption in refrigeration and air-conditioning leads to more fossil fuel consumption [1,2], increasing the emission of greenhouse gases [3–5]. To solve these problems, refrigeration technologies powered by renewable energy have been developed, e.g. ejection refrigeration, absorption refrigeration, adsorption refrigeration. Among them, people have paid more and more attention to ejection refrigeration systems due to its environmental-friendly characteristic, the use of the waste low-grade heat, which contains industrial waste heat, geothermal energy, solar energy [6,7], and other advantages including no moving parts, no lubrications, a potentially high reliability, relatively low capital cost, simplicity of operation, and low maintenance cost [8].

However, the COP of heat powered ejection refrigerator is at a low level, with a typical value of 0.2. Therefore, the usage of heat energy is not economically reasonable in refrigeration [9]. Besides, the traditional ejector refrigeration cycle cannot adapt to the changing operation environment, and cope with the impact of unsteady temperature of heat source. Fluctuations of the tempera-

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Nomenclature

A	surface area (m^2)
CERC	conventional compression-ejection refrigeration cycle
CERCE	compression-enhanced ejector refrigeration cycle with an economizer
COP	coefficient of performance
COP_g	global COP
COP_{th}	thermal efficiency
h	specific enthalpy (kJ/kg)
k	specific heat ratio
M	Mach number
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
R	gas constant (J/kg/K)
R_{cmp}	pressure ratio of compressor
s	specific entropy (kJ/kg/K)
T	temperature (°C)
p	pressure (kPa)
q	quality
$\dot{W}$	power (kW)
U	entrainment ratio
V	velocity (m/s)
η	efficiency
η_{power}	power plant efficiency
φ	ratio of fan out area
ρ	density (kg/m^3)

Subscript

c	condensing
cmp	compressor
d	diffuser
e	evaporating
ele	electric
g	generating
heat	converted heat
is	isentropic
jct	ejector
m	intermediate
mix	mixing section
n	normal shock
op	optimized
or	organic Rankine cycle
p	primary flow
p0	primary flow at inlet
prm	primary
pt	primary nozzle throat
px	primary flow at x section
py	primary flow at y section
pump	pump
s0	secondary flow at inlet
sc	supercool
sec	secondary
sh	superheat
sy	secondary flow at y section
t	throat
1–13	state point

Superscript

*	intermediate variable

ture of heat source results in a great change in efficiency and the intermittence in capacity of refrigeration [10]. In order to deal with the disadvantages of ejector refrigeration cycle, ejection cycles combined with compressor were employed to improve the cycle performance of refrigeration systems [11].

Sokolov et al. [12] introduced an enhanced ejector refrigeration cycle powered by low-grade heat, which can be also named as conventional compression-ejection refrigeration cycle (CERC). In this system (Fig. 1(a)), the high-pressure difference, between the secondary inlet and the exit of the ejector, was reduced by increasing the pressure of the vapor leaving the evaporator by mechanical compression. After that, they expanded the applicability of this system by enhancing the efficiency and thereby improving the economical attractiveness [13]. Dorantes [14] performed a simulation to evaluate the design of the system, not just for a whole day but for a whole year. The thermal COP of this system was 0.34, and the annual average value was 0.21. Hernandez [15] analyzed system performance using R142b and R134a as working fluid. The enhanced ejector refrigeration cycle working with R134a had the best operation with a highest coefficient of performance of 0.48 and an exergy efficiency of 0.25 at evaporating temperature (T_e) of −10 °C and generating temperature (T_g) of 85 °C. The system with R142b had its best performance at a higher generator temperature and condenser temperature. However, the energy efficiency decreased by 60% as condensing temperature increased by 10 °C. Mansour et al. [16] performed simulation studies on five thermodynamic cycles. The hybrid ejector-compressor booster achieved 21% COP improvement for using the same compressor over conventional mechanical compression cycle. Xu et al. [17] proposed a modified ejection-compression cycle to reduce the heat consumption and collector area. However, its mechanical COP is 19% lower than CERC, as only a small portion of compressor flow was leaded to the ejector to be compressed. Such a cycle can be also considered as ejector assisted compression cycle.

In 1997, Sun [9] studied another configuration of ejection-compression refrigeration cycle, which combined the two sub-cycles, namely an ejection sub-cycle and a compression sub-cycle. It combined the advantages and eliminated shortcomings of two kinds of cycles. The COP in this system could increase 50% compared with the traditional circle in theory. Huang et al. [18] introduced a combined-cycle refrigeration system which used ejector-cooling cycle as the bottom cycle. The experimental results showed that COP could be improved by 24% at largest for a combined-cycle refrigeration system when T_e was 5 °C. The cascade refrigeration cycle was investigated by Petrenko [19], which combined a mechanical compression refrigerating machine operated with CO_2, and an ejector cooling machine driven by waste heat with butane as the working fluid. The COP increased from 1.3 to 6.4, while T_e ranging from −40 to 0 °C. Chesi et al. [20] evaluated the potential advantages of integrating a solar powered ejection refrigerating system with a conventional vapor compression machine. Results showed the cascade system performs better than the ejection system cycle. A power consumption reduction of almost 40% is reached. A study on an ejection-compression cascade cycle using waste heat of the transport vehicle exhaust gas and CO_2 vapor compression sub-system was presented by Chen et al. [21]. At a boiler temperature of 120 °C, gas cooler outlet temperature of 35 °C, and T_e of −15 °C, the cascade cycle can improve electric efficiency by 60% at most. However, as the sub-cooler outlet temperature rises, the mechanical COP of the hybrid system is only 2.967. Bai [22] proposed an all-weather solar jet-variable compression cascade refrigerating method. The mechanical coefficient of