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Proposal and thermodynamic analysis of an ejection–compression refrigeration cycle driven by low-grade heat

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ABSTRACT

Ejection-compression refrigeration cycle reduces electricity consumption, by using huge quantity of low-grade heat, which increases equipment cost and occupies more space, especially when it is powered by solar heat. Hence, the large solar collector limits the practicability of ejection-compression refrigeration cycle. To solve this problem, a novel ejection-compression refrigeration cycle is proposed in this paper, which needs less heat and a smaller collector. It is theoretically compared to conventional vapor compression refrigeration cycle and conventional ejection-compression refrigeration cycle. It is also analyzed over wide temperature ranges. Results show that the proposed cycle has a COP 24% higher than conventional vapor compression cycle. The proposed cycle also has a COP 19% lower, heat transforming ratio 181% higher, and COP_g 144% higher than those of conventional ejection-compression cycle. With a collector 5 times smaller than a conventional ejection-compression cycle, the novel cycle is suitable for city buildings with limited space or economy sensitive users, although its COP is a little lower than conventional ejection-compression cycle. The effects of evaporating, condensing, generating, and intermediate temperatures (T_e, T_c, T_g, and T_m) on cycle performance are explained. At $T_m = 10$ °C, the maximum COP of 4.78 is obtained with the optimized generation temperatures of 72 °C.

1. Introduction

Vapor compression refrigeration cycle, consuming massive electric energy, is the most commonly used technology for space cooling and air-conditioning [1–3]. Heat driven refrigeration cycles [4,5], such as ejection refrigeration cycle, are good solutions for saving energy [6,7], which can be powered by solar heat or other low-grade heat. Especially, the ejector is simple, reliable and has a long life time. Like other heat driven refrigeration cycles [8–11], ejection cycle is limited by its poor efficiency, especially at low evaporation temperature. If ejection cycle is driven by solar heat, the low stability will also be a disadvantage.

Ejection–compression refrigeration cycle is therefore recommended in many studies to improve the efficiency and stability of the ejection cycle and also to consume less electric energy than vapor compression refrigeration cycle [12–14].

In 1990, Sokolov et al. [15] proposed an enhanced ejector refrigeration cycle powered by low-grade heat (Fig. 1), in which the vapor leaving the evaporator was boosted mechanically to reduce the high pressure difference between the secondary inlet and the exit of the ejector. A series of further investigation was carried out [16,17]. Hernandez et al. [18] analyzed an enhanced ejector refrigeration cycle with an intercooler theoretically, using R142b and R134a as working substance. An exergy efficiency of 0.25 was found at evaporation temperature of −10 °C and generation temperature of 85 °C. The above cycle was further studied by Arbel et al. [19]. To obtain 3.5 kW cooling capacity at 4 °C, the consumed low-grade heat was 6.74 kW provided by a 23.5 m^2 solar collector. Mansour et al. [20] performed a numerical evaluation of a hybrid ejector-compressor booster and cascade compressor-ejector cycle. The hybrid ejector-compressor booster revealed a highest COP when same compressor was used, which is 21% higher than that of conventional vapor compression cycle.

Another configuration of ejection-compression refrigeration cycle (Fig. 2) was investigated by Sun [21], which was a cascade cycle containing an ejection sub-cycle and a compression sub-cycle. The cascade cycle could increase the system COP about 50%. Petrenko et al. [22] studied a cascade CO_2 sub-critical mechanical compression/butane ejector cooling system driven by the heat of a cogeneration system. The results showed that the COP increased from 1.3 to 6.4 when the evaporation temperature

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Nomenclature

A	surface area (m^2)
COP	coefficient of performance
COP_g	global COP
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
Q	heat transfer rate (kW)
r	heat transforming ratio
T	temperature (°C)
p	pressure (kPa)
P	power (kW)
U	entrainment ratio
V	velocity (m/s)
x	quality
η	efficiency
η_{power}	power plant efficiency
ρ	density (kg/m^3)

Subscript

c	condensation
com	compressor
d	diffuser
e	evaporation
ele	electric
g	generation
i	cross section i of the ejector in Fig. 3
is	isentropic
j	cross section j of the ejector in Fig. 3
m	intermediate
mx	mixing
n	normal shock
p	primary flow
pump	pump
s	secondary flow
sc	subcool
sh	superheat
1–13	state point

Superscript

0	vapor compression system working at the same condition
*	sonic condition

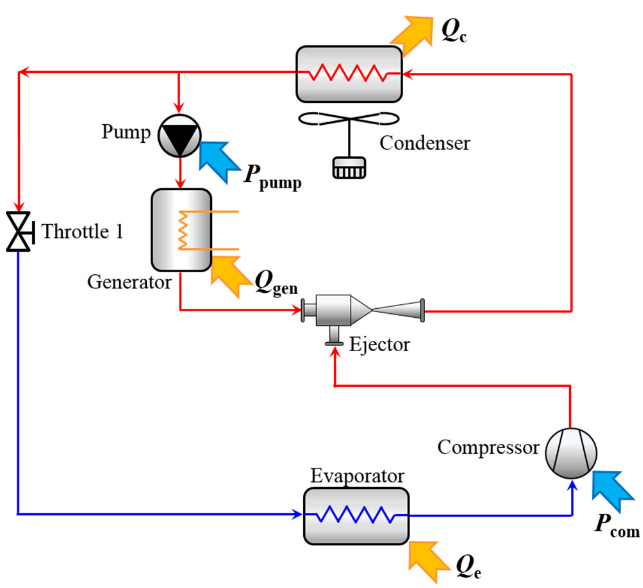

Fig. 1. Enhanced ejector refrigeration cycle.

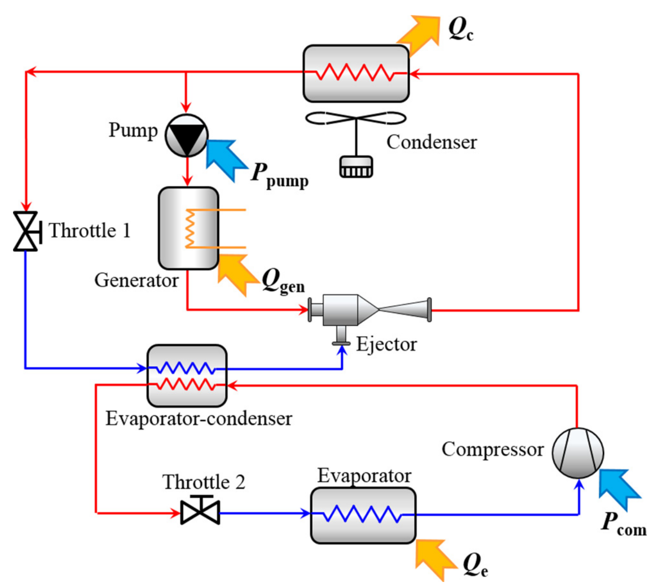

Fig. 2. Ejection-compression cascade refrigeration cycle.

varied from −40 to 0 °C. A study on the suitability of coupling a solar powered ejection cycle with a vapor compression refrigerating cycle was presented by Chesi et al. [23]. The results indicated that the ejection-compression cascade refrigeration cycle save more electricity energy than ejection refrigeration cycle. Chen et al. [24] investigated an ejection-compression cascade cycle driven by the waste heat of vehicle engine. With boiler temperature of 120 °C, 36.8% COP improvement was achieved. A hybrid ejector-vapor compression cycle (EVCC) was presented to improve the COP of the vapor compression refrigeration cycle (VCRC) in the study of Yan et al. [25]. On average, the COP improvement of the EVCC over the VCSC reaches 19.4%.

In addition, there is another typical configuration of ejection-compression refrigeration cycle as presented by Yan et al. [26] and Bai et al. [27]. The ejector is used as an expansion device to reduce the throttling losses and is not driven by heat energy. This cycle is essentially different from the aforementioned cycles and is not in the scope of this paper. Therefore, it will not be discussed here.

The above literature survey shows the good performance of ejection-compression refrigeration cycle. However, it can be calculated that to provide cooling capacity for space cooling of single square meter, a collector around 1.3 m^2 is needed when the cycle is powered by solar heat, according to the data from different literatures [17–21]. Especially, according to the optimization work reported by Vidal et al. [28], an ejection-compression system for a 10.5 kW cooling capacity was equipped with a 105 m^2 flat plate collector. Nevertheless, the above cooling capacity can only meet the need of space cooling for 50 m^2. These results show that the conventional ejection-compression refrigeration cycle consumes