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Refrigerant evaluation and performance comparison for a novel hybrid solar-assisted ejection-compression refrigeration cycle

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ABSTRACT

This paper presents an investigation on refrigerant evaluation and performance comparison of a novel solar-powered hybrid ejection-compression cycle for space cooling or refrigeration. By reducing heat consumption and solar collector area, the novel ejection-compression cycle can have better practicality and performance than conventional hybrid ejection-compression cycle. A model for the novel hybrid cycle is proposed including a validated 1-D ejector model. Five refrigerants are selected from a series of candidate refrigerants and are further evaluated based on cycle performance. Finally, R152a is recommended for its good characteristics and performance. With R152a, the novel cycle is compared with conventional cycle. The results show that the novel cycle has both higher electric efficiency (COP_{ele}) and thermal efficiency (COP_{th}), when rationally low solar heat is provided. At low heat region and $T_g = 90\,^{\circ}C$, the novel cycle only consumes 66.6 kW heat to increase COP_{ele} from 3.01 to 3.76, while the traditional cycle consumes 3 times the solar heat to achieve the same COP_{ele}. When more heat is consumed, the COP_{ele} of conventional cycle increases. However, the increasing installation space and capital cost of increasing collector greatly reduce the practicality of conventional cycle. Therefore, the novel cycle has better feasibility and good energy performance.

1. Introduction

Mechanical vapor compression refrigeration technology that is powered by high-grade energy is applied by most of the cooling and refrigeration systems at present (Song et al., 2017a; Du et al., 2016). The high consumption of high-grade energy doesn't meet the energy-saving requirement of modern society and it also contributes to the generation of greenhouse gases and air pollutants (Song et al., 2016, 2017b). Therefore, thermal compression refrigeration cycles which can be driven by low-grade heat, receive more attention, e.g. absorption, adsorption, and ejection refrigeration cycles (Zhou et al., 2017; Xu et al., 2016; Islam and Morimoto, 2016; Dennis et al., 2015).

Ejection refrigeration cycle has simpler configuration and lower capital cost than other heat driven cycles. It is also superior in compactness in manufacture and conveniences in operation and maintenance (He et al., 2015; Huang et al., 2011). Another advantage of ejection refrigeration cycle is its lower generating temperature, which allows it to harness solar energy more easily. The use of solar energy for cooling can further strengthen the energy-saving effect (Chen et al., 2017b; Varga et al., 2017). For instance, when weather is hotter, more refrigeration is usually required with constant humidity and there is simultaneously more solar energy to drive the ejector.

However, poor thermal efficiency and limits on off-design performance are two main drawbacks of ejection refrigeration cycle, which should be improved. Ejection-compression cycle, coupling a vapor compression refrigeration cycle with a solar powered ejector refrigeration cycle, is studied by many authors as a promising solution to overcome this issue (Yan et al., 2013; Vidal and Colle, 2010; and Chesi et al., 2013). Sun (1997) investigated a solar powered combined ejector vapor compression cycle for air conditioning and refrigeration. It was seen that the combined cycle can increase mechanical COP more than 50%, compared to vapor compression refrigeration cycle. The solar collector area needed for the combined cycle to produce 5 kW cooling was no more than 23 m^2. This area was relatively large, since it occupied most of the roof area of a 27.8 m^2 room for which a 5 kW air-conditioner was needed with estimated cooling capacity per square meter of about 180 W (Lu, 2008). Vidal and Colle (2010) reported a simulation and optimization work of a solar assisted combined ejector-vapor compression cycle for cooling application. The optimized system for a 10.5 kW cooling capacity was equipped with a 105 m^2 flat plate

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Nomenclature

A	cross section area (m^2)
COP_{ele}	electric COP (coefficient of performance)
COP_{th}	thermal COP (coefficient of performance)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
Q	heat transfer rate (kW)
T	temperature (°C)
p	pressure (kPa)
W	power (kW)
U	entrainment ratio
V	velocity (m/s)
x	quality
η	efficiency
ρ	density (kg/m^3)
φ	efficiency of fan-out area

subscript

c	condensation
cmp	compressor
d	diffuser
e	evaporation
g	generation
is	isentropic
m	intermediate
M^*	intermediate variable
mix	mixing
n	normal shock
prm	primary flow
p0	primary flow at inlet
pt	primary flow at throat
pump	pump
sec	secondary flow
s0	secondary flow at inlet
st	secondary flow at throat
sc	subcool
sh	superheat
t	throat
x	cross section x of the ejector in Fig. 2
y	cross section y of the ejector in Fig. 2
1–13	state point

collector. However, the collector area is much larger than the area of a room for which the 10.5 kW cooling system is suitable. A booster-assisted ejector refrigeration system combining an ejection system and a compression system was investigated by Zhao et al. (2016). Results showed that the mechanical COP of the combined system (7.746) was remarkably higher than vapor compression cycle at an optimum intermediate pressure of 630 kPa. Whereas the thermal COP of the combined system was still only 0.3 at the same working condition, indicating a very high consumption of low-grade heat. A large solar collector will be required if the system is powered by solar heat. A theoretical analysis of a cascade solar cooling system was presented by Chesi et al. (2013). The system including 100 m^2 of solar collectors and a 5 m^3 water thermal storage was able to increase the yearly COP of the conventional compressor system by 15%. With derived cooling capacity from the results, it can be found that the system fits a room only with approximately the same area of the collector (100 m^2).

From these references, existing ejection-compression refrigeration cycle greatly improves mechanical COP, whereas an often ignored disadvantage of its large solar collector is also exposed, which is usually as large as cooling area. Such a large collector means the system can only fit one floor. It cannot meet the requirement of modern cities with a lot of multi-storey buildings and high-rise buildings. Additionally, the expensive large collector stops the people living in countryside or developing countries from choosing ejection-compression refrigerator, even though they have lower builds. To overcome this problem, a novel hybrid ejection-compression refrigeration cycle was proposed. According to preliminary study (Xu et al., 2017), it may reduce the collector area by 4/5, comparing with conventional ejection-compression cycle and improve the COP by 24%, compared to vapor compression cycle.

The effects of refrigerant on cycle performance plays an important role on further study, design, and manufacturability of a refrigeration system, which involves the refrigerant impacts on both ejector and compressor and also the issue of refrigerant phase-out (Li et al., 2015). Chen et al. (2017a) presents the evaluation of the ejector refrigeration system with five environmentally friendly working fluids, namely R600, R600a, R601a, R1233zd(E) and R1234ze(E). By comprehensive comparisons, R1233zd(E) has generally higher system performance than the other four candidates. Sánchez et al. (2017) evaluated several low-GWP refrigerant as R134a alternatives, which was included in greenhouse gas basket by Kyoto protocol (French, 1997) and EU Directive 517/2014. From the energetic point of view, R290 obtained best results in a vapor compression refrigeration system and R152a also presented a good performance. Mota-Babiloni et al. (2017) reported an experimental assessment of R134a and its lower GWP alternative R513A. R513A, consisting of R134a and R1234yf, presented a higher cooling capacity and COP (5%) in vapor compression cycle. An efficiency analysis of eleven alternative refrigerants for ejector cooling cycles was presented by Gil and Kasperski (2015), which revealed that there was no single refrigerant that ensures efficient operation in the whole studied temperature range. Non-flammable synthetic refrigerants were suitable for low generating temperature, while organic solvents were suitable for higher generating temperature. Sun (1999) reported a performance comparison of ejector refrigeration cycle operating with various refrigerants. The analysis revealed that R152a had a better performance, while steam jet systems had poor COP. Lontsi et al. (2016) studied the performance of a multi-temperature compression-ejection refrigeration cycle with environment friendly refrigerants. Influences of refrigeration, freezing, and condensation temperatures on system performance were analyzed good performances of R290 and R152a were also observed.

However, most of the current refrigerant evaluation focus on ejector cycle or vapor compression cycle separately. The effects of refrigerants on the novel hybrid ejection-compression refrigeration cycle haven't been investigated yet, nor were suitable refrigerants selected for the new cycle. Accordingly, the aim of this paper is to analyze the promising refrigerants based on environmental characteristics, thermal properties, and energy performance in the novel ejection-compression refrigeration cycle. Based on the above analysis, appropriate refrigerant will be recommended for the proposed novel ejection-compression cycle. Finally, in term of energy performance, comparison between the proposed cycle and conventional ejection-compression cycle is presented with the selected refrigerant.

2. Cycle description and model

2.1. The proposed novel cycle

The schematic diagrams of a conventional hybrid ejection-compression refrigeration cycle (so-called compressor enhanced ejector cycle) and a novel ejection-compression refrigeration cycle are shown in Figs. 1 and 2.