

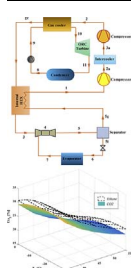
A comprehensive comparison between CO₂ and Ethane as a refrigerant in a two-stage ejector-expansion transcritical refrigeration cycle integrated with an organic Rankine cycle (ORC)

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GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, the performance of a two-stage ejector-expansion transcritical refrigeration cycle using ethane and CO₂ as refrigerant is investigated. The theoretical analysis of cycle performance characteristics is carried out for both refrigerants from the first and second laws of thermodynamics viewpoints. Furthermore, a supercritical ORC is utilized for waste heat recovery of gas-cooler. Based on the results, it is found that the COP and second law efficiency for the ethane refrigerant are about 9.37 and 9.43% higher than that of the CO₂. Moreover, the compressor discharge temperature for ethane compared to the CO₂ in two-stage ejector-expansion transcritical refrigeration cycle is about 17–25% lower, which leads to a higher lifetime of the compressors for ethane. It is also concluded that the gas-cooler waste heat recovery improves the CO₂ cycle performance more than ethane due to its higher potential for waste heat recovery.

1. Introduction

Refrigeration system performance enhancement is an emerging research topic to reduce the electricity consumption, leading to mitigate the environmental pollution problems related to utility of power plants [1]. Vapor compression refrigeration is a well-known system in which the refrigerant undergoes phase changes. This system is the most widely used method for air-conditioning and refrigeration [2]. Many attempts have been done for this system's performance enhancement in the recent years. Some of the main researches in this criteria are using ejector,

proper selection of refrigerant, cycle configuration and operating condition improvement and finally, utilizing the potential waste heat of the high temperature sources in the cycle.

Using an ejector as the expansion device instead of the expansion valve can improve the performance of a conventional compression refrigeration cycle [3]. The ejector is a device which uses a high-pressure fluid for pumping a low-pressure fluid to a higher pressure level. Ejector's no moving parts, low cost and ability to handle two-phase flow without destruction make it a beneficial device for being the expansion device in refrigeration systems [4]. An ejector could reduce both

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Nomenclature

COP	Coefficient of performance [–]
h	Specific enthalpy [kJ/kg]
hex	Internal heat exchanger
$\dot{i}$	Exergy destruction rate [kJ/s]
IC	Inter cooler
$\dot{m}$	Mass flow rate [kg/s]
P	Pressure [bar]
$\dot{Q}$	Heat transfer rate [kJ/s]
s	Specific entropy [kJ/kg K]
T	Temperature [°C]
ν	Velocity [m/s]
U	Entrainment ratio [–]
$\dot{W}$	Work [kJ/s]
x	Quality [%]
η	Efficiency [%]
ψ	Specific exergy [kJ/kg]

Subscripts

amb	Ambient
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0	Reference environment
1,2,...	Cycle locations
c	Compressor
gc	Gascooler
ej	Ejector
d	Diffuser
n	Nozzle
m	Mixing
e	Evaporator
rev	Reversible process
EV	Expansion valve
p	Pump
T	Turbine
cond	Condenser
s	Isentropic process
t	Total
r	Refrigerated object
2	Second law
i	Inter-stage pressure

expansion irreversibility and the compression work (raising the suction pressure), which leads to the system performance improvement [3].

Generally, an appropriate refrigerant for a refrigeration system should be able to provide high performance for the required operating conditions. The refrigerant thermo-physical properties play a significant role in the performance enhancement [3]. Potential refrigerants, which are not applicable due to large expansion valve losses in a conventional vapor compression refrigeration system, may be much more appealing when used in an ejector expansion cycle [1]. Refrigeration cycle configuration and operating condition improvement are other ways for the system efficiency enhancement. One of the practical operating conditions is transcritical condition. In the transcritical ejector refrigeration system (TERS) a refrigerant operates over the critical circumstances of the refrigerant. CO₂ refrigerant has a low critical temperature and therefore, is one of the appropriate refrigerants for transcritical cycles [5]. One of significant defects of the transcritical CO₂ refrigeration system is its large pressure difference across the compressing process, which leads to a lower first and second law efficiency [6]. One ejector CO₂ TERS, One ejector CO₂ using a two-stage compressor and intercooler between them, two ejector CO₂ TERS and CO₂ TERS with an internal heat exchanger are the main efforts for the applicability enhancement of a transcritical refrigeration system [3]. In the transcritical CO₂ refrigeration cycles, CO₂ working fluid which is compressed, must be cooled in the gas cooler. The temperature range of CO₂ working fluid discharging from the compressor is about 100–200 °C, which should be cooled down to around 35–55 °C in the gas cooler. This is the wasted energy of this cycle and a potential thermal energy source which can be used in supercritical CO₂ cycles for power generation purposes [5].

As mentioned before, refrigeration cycle working fluid has an important role on the system performance. Kornhauser [7] has performed the first investigation about using different working fluids (R11, R12, R22, R113, R114, R500, R502 and R717) in an ejector expansion refrigeration system (EERS). The improvement in COP with the ejector expansion system was different for various refrigerants, because the sources of loss in the standard vapor-compression cycle varied (by 12–30%). Nehdi et al. [8] compared different refrigerants and their results showed that, R141b as the working fluid leads to the highest improvement in COP (22%). Sarkar [9] compared natural refrigerants (R290, R600a, and R717) and observed that using R600a leads to the maximum performance enhancement. Ersoy and Sag [10] verified a

R134a EERS and concluded that the COP was 6.2–14.5% higher than that of the conventional system, depending on the operating conditions.

Boumaraf et al. [11] reported a COP improvement about 17% for the condenser temperature of 40 °C for both R134a and R1234yf (which is an alternative for R134a). R1234yf was found to have higher COP, especially at high condenser temperatures. Also, Lawrence et al. [12] compared EERS with conventional systems and reported an improvement in COP up to 6% with R1234yf and 5% with R134a.

Many researches have been done on the cycle configuration of the transcritical ejector refrigeration system (TERS) improvement in recent years. Li and Groll [13] investigated theoretically a CO₂ TERS cycle with ejector-expansion device and found that the ejector expansion cycle leads to an improvement about 16% in COP compared to the basic cycle. Deng et al. [14] analyzed a CO₂ TERS cycle thermodynamically and found that an improvement of 22% in the COP achieved compared to a standard cycle. Yari and Sirousazar [15] presented a new refrigeration cycle with an ejector, internal heat exchanger and intercooler. Based on their results, the COP and exergy efficiency values of the new cycle are about 8.6 and 8.15% more than that of the conventional cycle with R125 refrigerant as the working fluid. In another work, they [16] proposed a new transcritical CO₂ refrigeration (TRCC) cycle with an ejector, internal heat exchanger and intercooler and found that, the new cycle improves the maximum COP and second law efficiency up to 26% compared to the conventional one. Furthermore, Yari [4] proposed correlations to predict the design parameters of a new two-stage ejector expansion TRCC cycle. This study results showed that the new cycle maximum COP and second law efficiency are about 12.5–21% higher than the conventional one. Fangtian and Yitai [17] compared a CO₂ TERS with an ejector and a throttling valve: the ejector cycle increased the COP about 30% and reduced the exergy loss by more than 25%. Bai et al. [18] studied a CO₂ TERS cycle with a sub cooler and concluded that the proposed cycle COP is up to 7.7% higher than the conventional vapor injection cycle. He et al. [19] optimized the performance of a transcritical CO₂ refrigeration cycle by a controlled ejector and concluded that the optimal controller is verified by experiments to be an effective way to improve the system performance automatically. An experimental evaluation of a CO₂ transcritical refrigeration plant with dedicated mechanical sub-cooling is carried out by Llopis et al. [20]. Their results showed that the increments on capacity at the maximum measured COP conditions ranged from 23.1 to 39.4% at an evaporating level of 0.0 °C and from 24.2 to 55.7% at

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