Energy Proceedings
Vol 28, 2022
ISSN 2004-2965

Thermodynamic analysis of a transcritical CO_2 system with ejector and integrated mechanical subcooling for heating and cooling

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ABSTRACT

A transcritical CO_2 heat pump-air conditioning system with ejector and integrated mechanical subcooling (EJ-IMS) is proposed for heating and cooling. The energetic and exergetic performance are discussed compared with baseline transcritical CO_2 system (BASE), conventional transcritical CO_2 with ejector (EJ), and transcritical CO_2 system with integrated mechanical subcooling (IMS). The results indicate a maximum coefficient of performance (COP) is achieved for EJ-IMS, which is improved than other studied systems. EJ-IMS can significantly reduce the optimum discharge pressure. The compressor and gas cooler show the highest irreversible loss. EJ-IMS shows the best annual performance factor (APF), and Haikou has the highest APF.

Keywords: CO_2, integrated mechanical subcooling, ejector, annual heating and cooling, energetic and exergetic analysis

NONMENCLATURE

Abbreviations	
APF	Annual performance factor
BASE	Baseline transcritical CO_2 system
COP	Coefficient of performance
Com	Compressor
Evap	Evaporator
EJ	Ejector, Conventional transcritical CO_2 with ejector
EJ-IMS	Transcritical CO_2 with EJ and IMS
GC	Gas cooler
IMS	Integrated mechanical subcooling, Transcritical CO_2 system with IMS
SC	Subcooler
Symbols	
0	Ambient
1-17,3r	State point
a	Air
c	Cooling
D	Destruction
e	Exergy
h	Heating
w	Water

1. INTRODUCTION

Building is one of the three major areas of energy consumption in China and an important source of CO_2 emissions [1]. The building energy consumption of China accounts for 5% of total energy-related carbon dioxide emissions for the globe [2]. Meanwhile, the energy consumption of air conditioning, heating, and domestic hot water exceeds 60% of building energy consumption in China [3]. The energy consumption structure of China is mainly based on fossil energy, such as coal, oil, and natural gas. Therefore, the energy transformation, such as replacing coal-fired boilers with heat pumps is an important way to promote the peak of carbon emissions in China by 2030 [4]. Moreover, in response to the Kigali Amendment [5], CO_2 is considered an environmentally friendly working fluid to replace the traditional refrigerant. Therefore, CO_2 heat pump and refrigeration system is a promising application for heating or cooling.

For the high efficiency and safe operation of CO_2 heat pump and refrigeration, there are many effective methods to utilize, such as parallel compression, subcooling, ejector, and so on. The ejector can substitute the expansion valve to recover part of the expansion work during throttling and significantly reduce the compression ratio and discharge temperature of the compressor. Expósito-Carrillo et al. [6] proposed the optimization methodology for the operating conditions in a CO_2 refrigeration cycle and found the parallel compressor combined with ejectors improves the efficiency in warm climates, which is up to 13% higher COP than the system without ejector. Bai et al. [7]

presented that ejector enhanced the sub-cooler vapor injection CO_2 heat pump cycle, and found the improvement of the volumetric heating capacity and COP could reach up to 9.5% and 7.7%, respectively compared with the CO_2 heat pump system without ejector. The subcooling takes many forms, the integrated mechanical subcooling (IMS) is mostly concentrated in recent years. The IMS could increase the specific cooling capacity and reduce the optimum working pressure. Although the addition of a second compressor, the COP of the cycle can be enhanced. Khan et al.[8] developed thermodynamic models of an integrated mechanical subcooling system, and found the performance of the new system is improved over the corresponding basic cycle. Catalán-Gil et al. [9] compared the dedicated and integrated mechanical subcooled CO_2 boosters in the supermarket application, and they found the integrated subcooling system can reduce annual energy by 1.3%-4.0% in different regions. Nebot-Andres et al. [10] tested the performance of the integrated mechanical subcooling cycle under different heat rejection temperatures and found the COP could be improved by 4.1%, 7.2%, and 9.5% at 25.0°C, 30.4°C, and 35.1°C, respectively compared with parallel compressor system.

In conclusion, both ejector and integrated mechanical subcooling can significantly improve the cooling and heating performance of CO_2 transcritical systems. However, most studies focus on the single energy supply mode, heating or cooling, especially for cooling. Moreover, the energy supply performance when the ejector and integrated mechanical subcooling are combined is seldom considered. Therefore, a transcritical CO_2 heat pump-air conditioning system with ejector and integrated mechanical subcooling (EJ-IMS) is proposed, which utilizes multiple three-way valves to convert between heating and cooling modes and compared with baseline transcritical CO_2 system (BASE), conventional transcritical CO_2 with ejector (EJ), and transcritical CO_2 system with integrated mechanical subcooling (IMS). Afterward, COP and discharge pressure are discussed by energy analysis. Then the exergy destruction of each component is analyzed. Finally, the annual performance factor (APF) of the systems is discussed in eight typical cities with different climatic conditions. This study can provide a theoretical reference for improving the performance of transcritical CO_2 systems in cooling and heating and the application of transcritical CO_2 systems in different climate regions.

2. CYCLE MODELING

2.1 Cycle description

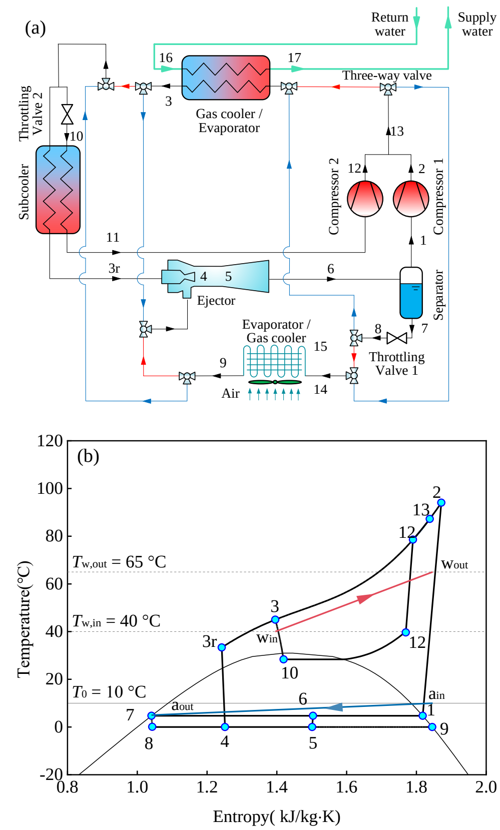


Fig. 1 T-s diagram of transcritical CO_2 heat pump-air conditioning system with EJ and IMS (EJ-IMS) (a) Schematic. (b) T-s diagram.

Fig. 1 depicts the system diagram and *T-s* diagram of transcritical CO_2 heat pump-air conditioning system with EJ and IMS (EJ-IMS), which is consist of two compressors, a gas cooler, an evaporator, an ejector, a separator, two throttling valves, and multiple three-way valves. The CO_2 flows into the compressor as saturated vapor from the separator and is compressed to superheated steam by compressor 1 (1-2). Afterward, it is mixed with the high-temperature and high-pressure CO_2 from compressor 2, then the mixed fluid is cooled by the water through the gas cooler (13-3) and heat the water at the same time (16-17). Then it is divided into two parts at the outlet of the gas cooler, the first part of CO_2 flows into the subcooler after being throttled by the throttle valve 2 (3-10-11) to recool the second part of CO_2 flowing through the gas cooler (3-3r). After the auxiliary heat absorption in the subcooler, the first part of CO_2 flows into compressor 2 and is compressed to the same pressure as the inlet of the gas cooler (11-12). The second part of CO_2 flowing from the subcooler as the primary fluid with high pressure enters the nozzle (3r-4) and is mixed with the secondary fluid entrained by the primary fluid (9-4) in the mixing section (4-5). Subsequently, the mixing fluid is pressurized in the diffusion section (5-6) and then flows into the separator. The saturated liquid (6-7) throttles through the throttling valve 1 (7-8) then flows into the evaporator (8-9) and absorbs heat from the environment (14-15), the saturated vapor is sucked back into the compressor 1 (6-1) and the cycle is finished. The use of multiple three-way valves can realize the conversion between cooling and heating modes in EJ-IMS.

In addition, there are three systems for comparison, which are BASE, IMS, and EJ, respectively.

2.2 Assumption of the model

The model is established on the following assumptions:

(1) The system operates under steady conditions, and the heat loss and pressure drop of refrigerant in the heat exchanger and tube are ignored.

(2) The refrigerant at the outlet of the evaporator and separator are both in the saturated state.

(3) The mechanical and motor efficiency of the compressor are both 1, and the isentropic efficiency of the compressor depends on its pressurization ratio.

(4) The pinch point temperature difference of the gas cooler, subcooler, and evaporator is 5°C, respectively [7].

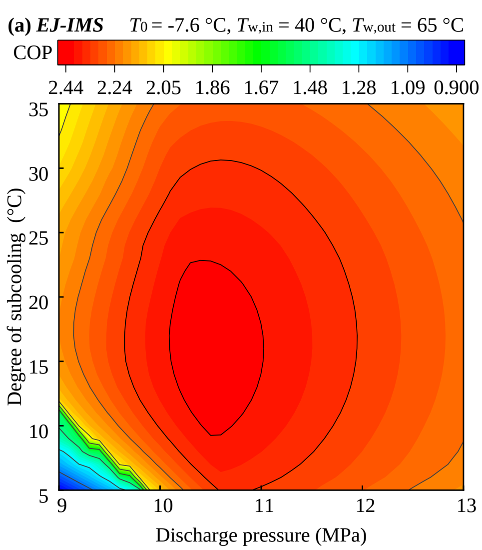
(5) The inlet and outlet water temperatures are 40°C and 65°C, respectively in the heating season, and 12°C and 7°C, respectively in the cooling season.

(6) The fluid flows in the ejector in a one-dimensional steady-state, and the fluid kinetic energy at the ejector inlet and outlet is ignored [11].

(7) The primary and secondary fluids are mixed in the mixing section at constant pressure.

(8) The ejector nozzle efficiency is 0.8, the mixing chamber efficiency is 0.95, and the diffuser efficiency is 0.8 [12].

3. RESULTS AND DISCUSSION



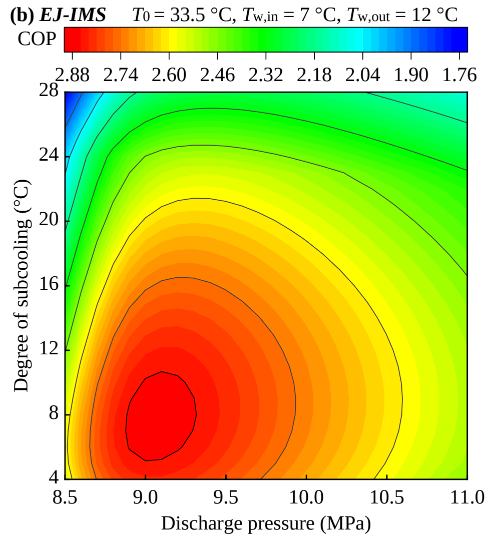


Fig. 2 COP variation with discharge pressure and subcooling degree in heating and cooling mode. (a) Heating mode. (b) Cooling mode.

The variations of COP with discharge pressure and subcooling in heating and cooling modes of EJ-IMS are shown in Fig. 2. It can be observed that the maximum COP is 2.43 at a discharge pressure of 10.4 MPa and a subcooling temperature of 16°C in Fig. 2(a), which are named optimal discharge pressure and subcooling temperature in this study, respectively. Similarly, when the discharge pressure is 9.1 MPa as well as the subcooling degree is 8°C in cooling mode, the maximum COP reaches 2.87 in Fig. 2(b). Furthermore, when the discharge pressure is constant, COP increases first and then decreases with the increase of subcooling temperature, and when the subcooling temperature is constant, COP shows the same trend described above with the increase of discharge pressure. Therefore, it can be concluded that the discharge pressure and the subcooling temperature are important factors affecting the performance of the EJ-IMS.

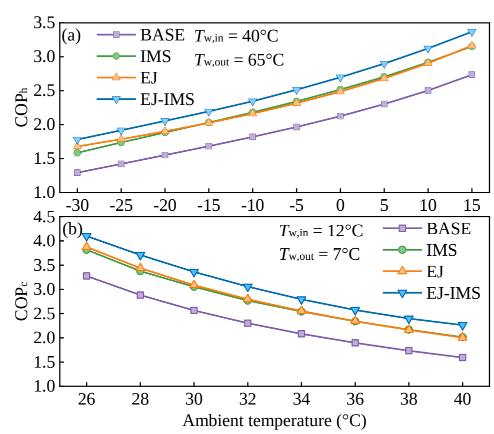


Fig. 3. Optimal COP variation with ambient temperature. (a) Heating mode. (b) Cooling mode.

The optimal COP variations with ambient temperature in heating and cooling modes are exhibited in Fig. 3. It can be seen that COP increases in the heating mode (T<18°C) and decreases in the cooling mode (T>26°C) with the rise of ambient temperature, respectively. It can be noted that the COP of EJ-IMS changes from 4.10 to 2.26 and 1.78 to 3.37 in heating mode and cooling mode, respectively, which shows the best performance among the four kinds of systems. Moreover, the COP of EJ-IMS is 23.2%-37.7% and 25.1%-42.2% higher than the BASE in heating mode and cooling mode, respectively. This is because part of the expansion work can be recovered with the introduction of the ejector, and the power consumption by the compressor can be reduced. At the same time, the specific cooling capacity can be increased by the introduction of subcooling. Hence, EJ-IMS can significantly improve performance in both cooling and heating modes.

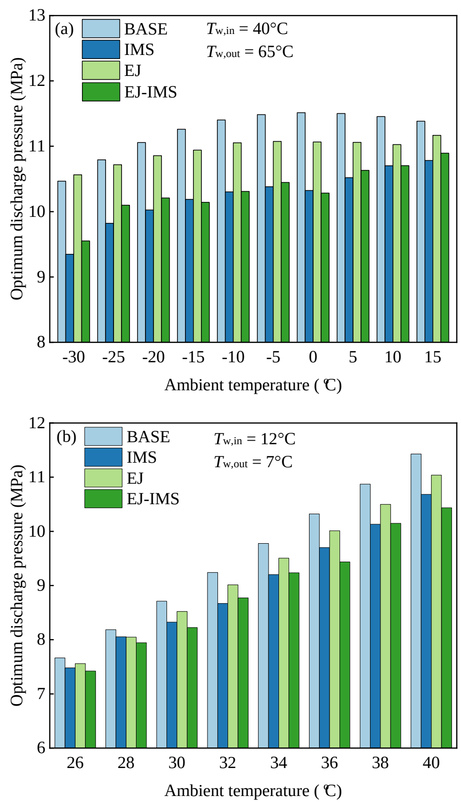


Fig. 4 Optimal discharge pressure variation with ambient temperature. (a) Heating mode. (b) Cooling mode.

Fig. 4 shows optimal discharge pressure variation with ambient temperature in heating and cooling mode. It can be observed that the optimum discharge pressure of EJ-IMS is 4.29%-10.69% and 2.94%-8.68% in heating mode and cooling mode, respectively compared with that of the BASE. EJ-IMS shows the lowest optimum discharge pressure in both kinds of modes under most of the studied conditions. Moreover, the optimal discharge pressure of IMS and EJ is less than that of the BASE, which means the introduction of ejector and integrated mechanical subcooling can effectively reduce the optimal discharge pressure of the system, and the integrated mechanical subcooling has greater advantages over ejector. Besides, in the cooling mode, the discharge pressure increases with the rise of ambient temperature, while in the heating mode, the discharge pressure fluctuates slightly, but the overall trend is on the rise. The variation trend of the optimal discharge pressure with ambient temperature in heating mode is slower than that in cooling mode.

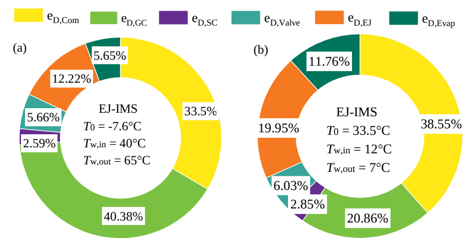


Fig. 5 Exergy loss of EJ-IMS. (a) Heating mode. (b) Cooling mode.

The exergy loss of EJ-IMS in heating mode (T_0=-7.6°C) and cooling mode (T_0=33.5°C) are shown in Fig. 5. It can be noted that the compressor and gas cooler show the highest irreversible loss both in heating mode and cooling mode, which two items together account for 73.88% and 59.41% of the total, respectively. Meanwhile, the subcooler has the lowest exergy loss, only 2.59% and 2.85% in heating mode and cooling mode, respectively. Due to the introduction of two compressors, the compressor accounts for the largest exergy loss in the cooling mode, which is 38.55%. However, the gas cooler accounts for the highest irreversible loss in the heating mode, which is 40.38%, and the exergy loss of the compressor is the second. Therefore, the exergy destruction of the compressor and gas cooler should be reduced firstly to improve the performance of the system.

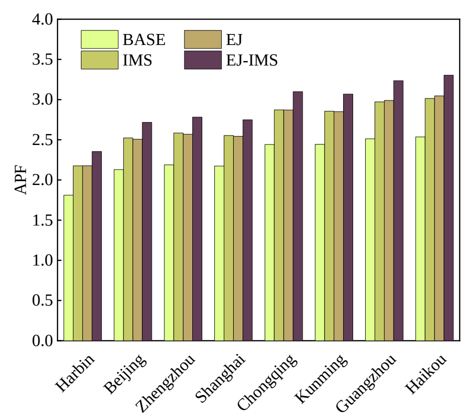


Fig.6 Annual performance factor in different cities.

Fig.6 shows the annual performance *factor* for different systems in eight typical cities. It can be seen that EJ-IMS shows the best APF among the four systems, which is 30.00%, 27.61%, 27.19%, 26.46%, 26.92%, 25.55%, 28.79%, and 30.33% higher compared with BASE, respectively. Furthermore, APF decreases with the rise of urban latitude. Therefore, Harbin shows the smallest APF of 2.35 with EJ-IMS, while Haikou has the highest APF, which is 3.30 with EJ-IMS. This is because refrigeration performance is better than the heating performance of studied systems, while refrigeration time in Haikou is longer than in other cities, which indicates that the whole systems have better working performance and a higher energy saving rate in low latitudes. Especially for EJ-IMS, it can significantly improve system performance.

CONCLUSION

A transcritical CO_2 heat pump-air conditioning system with ejector and integrated mechanical subcooling is proposed for heating and cooling. In this study, the energetic and exergetic performances are discussed compared with BASE, EJ, and IMS. The conclusions are shown as follows:

(1) A maximum COP is achieved for EJ-IMS at optimal discharge pressure and optimal subcooling temperature.

(2) The COP of EJ-IMS changes from 4.10 to 2.26 and 1.78 to 3.37, which is 23.2%-37.7% and 25.1%-42.2% higher than the BASE in heating mode and cooling mode, respectively.

(3) The application of ejector and IMS in EJ-IMS can reduce the optimum discharge pressure, which is 4.29%-10.69% and 2.94%-8.68% in heating mode and cooling mode, respectively compared with that of the BASE.

(4) The compressor and gas cooler show the highest irreversible loss both in EJ-IMS.

(5) EJ-IMS shows the best APF among the four systems, which is 25.55%-30.33% higher compared with BASE in different cities, and Haikou has the highest APF.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support from the National Key Research and Development Program of China (No. 2021YFE0116100), National Natural Science Foundation of China (No. 51806151), Tianjin Natural Science Foundation (No. 20JCQNJC00600), Technical Service of HCFC Phase-out Management Plan Stage II for Industry of Room Air-conditioner and Household Heat Pump Water Heater for FECO/MEE (No. FECO/LY1/S/21/171), and the Innovation Team of Cold Chain Units, Energy Saving and Cold Storage of College and the University of Tianjin Municipality (No. TD13-5088).

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