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Research Paper

Theoretical analysis of a transcritical double-stage nitrous oxide refrigeration cycle with an internal heat exchanger

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HIGHLIGHTS

- Three transcritical N_2O refrigeration cycles are investigated theoretically.
- Thermal performance is compared to that of similar cycles using CO_2.
- The N_2O DSCI cycle has the highest optimum COP.
- Correlations of the optimum pressures are obtained for the three cycles.

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ABSTRACT

Thermodynamic analysis and optimization studies are performed on three transcritical nitrous oxide refrigeration cycles including a single-stage compression (SSC) cycle, a double-stage compression (DSC) cycle and a double-stage compression with an internal heat exchanger (DSCI) cycle. The thermodynamic performance is compared with that of similar cycles using CO_2. The results show that the N_2O SSC and DSC cycles exhibit a larger optimum COP and a lower discharge pressure compared with the CO_2 cycles at given conditions. For the DSC cycle, there exists an optimum COP at certain gas cooler high pressure and intermediate pressure for both working fluids. The double-stage compression and the internal heat exchange have a significant effect on the optimum COP enhancement for N_2O transcritical refrigeration cycles. Further, the introduction of the internal heat exchange can also reduce the optimum pressure for the N_2O DSC cycle. The comparison between the three cycles shows that the N_2O DSCI cycle has the highest optimum COP. Correlations of the optimum gas cooler high pressure and the intermediate pressure are proposed in terms of the gas cooler exit temperature and the evaporating temperature for the three cycles.

1. Introduction

In recent years, several natural refrigerants such as carbon dioxide, nitrous oxide, air, water, ammonia and propane have received increasing attention as future refrigerants in the field of refrigeration and air conditioning [1]. As an earliest natural refrigerant, carbon dioxide (CO_2 or R744) has been widely acknowledged due to its good properties such as excellent thermal physical properties, non-toxicity, no flammability, low cost, and environmental safety. Nitrous Oxide (N_2O), which has similar thermodynamic properties as CO_2, is also a promising natural refrigerant. It is shown in Table 1 that the system characteristics such as system temperature, pressure and properties of N_2O cycle are similar to that of CO_2 cycle due to the similarity of critical temperature, critical pressure and molecular weight between N_2O and CO_2. As time goes on, the CO_2 transcritical cycle has been widely used in many applications such as automobiles, water heaters, heat pumps and low temperature cascade refrigerators. However, N_2O systems have not been well studied. The working temperature range of a refrigerant depends on its triple point temperature. As shown in Table 1, N_2O can be used at an evaporating temperature as low as -90.82 °C, but CO_2 can only be used at an evaporating temperature above -56.56 °C. Another advantage of N_2O is that its toxicity is more favorable compared with CO_2. Although the GWP of N_2O is significantly higher than that of CO_2, its value still falls in the range of low GWP classification according to a report of the United Nations Environment Programme [2].

Due to the high throttling loss, the energy efficiency of the basic transcritical CO_2 cycle is relatively lower than that of the conventional vapor compression refrigeration cycle, and the issue has become a

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Nomenclature

COP	coefficient of performance [–]
IHX	internal heat exchanger [–]
ODP	ozone depletion potential [–]
GWP	global warming potential [–]
h	specific enthalpy [kJ kg^{-1}]
s	specific entropy [kJ kg^{-1} K^{-1}]
w	specific work [kJ kg^{-1}]
P	pressure [bar]
T,t	temperature [°C]
q	specific heat transfer rate [kJ kg^{-1}]
SSC	single-stage compression [–]
DSC	double-stage compression [–]
DSCI	double-stage compression with internal heat exchanger [–]
LP	low pressure [–]
HP	high pressure [–]

Greek symbols

η	efficiency [%]
ε	efficiency [%]

Subscripts

c	compressor
opt	optimum
h	high
int	intermediate
ev	evaporator
gc	gas cooler
is	isentropic
1,2,3,…	state point

major concern [3]. Some modifications of the basic cycle, such as using an expander or an ejector to replace the throttling valve and the use of double-stage compression, have been investigated [4–8]. Elbel and Hrnjak [4] experimentally studied the performance of a transcritical CO_2 ejector expansion refrigeration cycle with an internal heat exchanger (IHX), and they showed that the COP was improved by 7% over the simple throttle valve cycle with an IHX. Zhang et al. [5] theoretically analyzed the effect of IHX on the performance of the ejector expansion transcritical CO_2 refrigeration system and found that the use of IHX did not always improve the system performance in the ejector expansion cycle. Yang et al. [6] performed a theoretical analysis of three different double-stage CO_2 transcritical refrigeration cycles and found that both the use of double-stage compression and the use of an expander could improve the system performance. It was reported that the COP of a two-stage compression cycle was on average 9% higher than that of a single-stage compression cycle. Cecchinato et al. [7] performed a theoretical analysis on different double-stage CO_2 transcritical refrigeration cycles. Optimization methods for different cycles were proposed. Agrawal et al. [8] presented a thermodynamic analysis of three double-stage transcritical CO_2 heat pump cycles.

IHX is often employed in refrigeration systems to improve the cycle performance. The applications and performance analysis of IHX in transcritical CO_2 cycles have been extensively studied [9–15]. Kim et al. [9] performed a theoretical analysis of a transcritical CO_2 cycle with an internal heat exchanger for hot water heating. Aprea and Maiorino [10] presented experimental studies of a transcritical CO_2 refrigerator using an internal heat exchanger and the results showed that the system coefficient of performance was improved by using an internal heat exchanger. Cho et al. [11] experimentally investigated the performance improvement of a CO_2 cycle with an internal heat exchanger. A similar study was carried out by Tao et al. [12]. Chen and Gu [13] performed a theoretical analysis of the optimum high pressure for a transcritical CO_2 cycle with an internal heat exchanger. The use of an internal heat exchanger does not necessarily improve the system COP. Shariatzadeh et al. [14] analyzed four transcritical CO_2 refrigeration cycles and showed that the use of internal heat exchanger in conjunction with expander reduced the system COP. Zhang et al. [15] also found that the use of IHX did not always improve the system performance in the CO_2 refrigeration cycle with an expander.

Table 1
Comparison of N_2O and CO_2 properties [16].

Properties	N_2O	CO_2
ODP	0	0
GWP	240	1
Critical temperature (°C)	36.4	31.1
Critical pressure (bar)	72.5	73.84
Toxicity (ppm)	1000	5000
Triple point temperature (°C)	−90.82	−56.56
Molecular weight (g/mol)	44.013	44.01
Latent heat of vaporization* (kJ/kg)	204.93	213.97

* The latent heat of vaporization values are calculated at the pressure of 4 MPa.

Compared with the studies on CO_2 cycles, research on the refrigeration system using N_2O as refrigerant is relatively lack of attention in literature. Kruse and Russmann [16] performed a theoretical analysis of the optimum COP for a cascaded refrigeration system using N_2O as the low temperature stage refrigerant. The other cascaded system using N_2O as low temperature fluid was investigated by Bhattacharyya et al. [17]. Dayma et al. [18] performed a theoretical analysis of a transcritical N_2O heat pump system via the discharge pressure optimization. Sarkar and Bhattacharyya [19] investigated a single-stage compression transcritical N_2O refrigeration cycle to determine the maximum COP. Choudhary et al. [20] reported a theoretical investigation on a single-stage compression N_2O refrigeration cycle with an ejector. It is found that modifications of the basic single-stage cycle such as the use of double-stage compression and internal heat exchange have not been studied for the transcritical N_2O refrigeration system. Effects of using double-stage compression and internal heat exchange on performance of the N_2O refrigeration system remains unknown. The study on performance of the transcritical N_2O double-stage compression cycle with an internal heat exchanger is very limited in literature.

In order to further improve the thermodynamic efficiency of the transcritical N_2O refrigeration system, thermodynamic analyses and optimization studies are performed on three N_2O refrigeration cycles including a single-stage compression (SSC) cycle, a double-stage compression (DSC) cycle and a double-stage compression with an internal heat exchanger (DSCI) cycle. In the present work, thermodynamic analyses are presented to determine the maximum COP and the optimum discharge pressure of the three transcritical N_2O cycles. Comparative analyses of the three transcritical N_2O cycles are carried out. Correlations of the optimum discharge pressure are proposed in terms of the evaporating temperature and the gas cooler exit temperature. Performance comparison is also performed in the similar transcritical cycle using CO_2 as refrigerant.

2. System description and thermodynamic modeling

2.1. System description

The schematic and the corresponding temperature-entropy diagrams of the transcritical N_2O single-stage compression (SSC) cycle are