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Thermodynamic analysis of a transcritical CO_2/propylene (R744–R1270) cascade system for cooling and heating applications

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In this paper natural refrigerant propylene (R1270) has been proposed for transcritical cascade refrigeration system and analyzed. Propylene is used in the low temperature (LT) cycle and carbon dioxide is used in the high temperature (HT) cycle of the cascade transcritical refrigeration system. The proposed transcritical cascade cycle can be used for simultaneous cooling and heating applications. Thermal performance of the cascade cycle is evaluated for different combinations of design and operating variables and optimum performance parameters such as T_{opt}, COP_{max} and mass flow of propylene and CO_2 have been predicted. Design parameters include the evaporator temperature of LT cycle (T_E), gas cooler outlet temperature (T_C) and cascade heat exchanger temperature difference (DT). The results of the analysis show better thermal performance of CO_2–propylene transcritical cycle than subcritical cascade cycle and also better than N_2O–CO_2 transcritical cycle. A methodology to obtain relevant performance diagrams and regression correlations to serve as a guideline for the design and optimization of transcritical CO_2–propylene cascade system has been developed.

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1. Introduction

Environmental problems like global warming and depletion of the ozone layers caused by the use of synthetic refrigerants have become severe over the last decade. During this period, the refrigeration, air conditioning and heat pump industry have been forced through major changes caused by restrictions on the use of synthetic refrigerants. The changeover to ozone friendly chlorine free substances is not finished yet as the HCFC fluids still need to be replaced.

Two stage cascade refrigeration systems are suitable for industrial applications such as cryogenic separation in petrochemical industries, liquefaction of petroleum vapors and natural gas, manufacturing of dry ice, precipitation hardening of special alloy steel and storage of food, blood etc. In these systems two single stage units are thermally coupled through the cascade heat exchanger. The low temperature circuit of a transcritical cascade refrigerant system can normally be charged with N_2O, propane (R290), propylene (R1270), and ethane (R170) for cooling whereas, carbon dioxide (R744) is used in the high temperature circuit for heating applications. In subcritical cascade system ammonia (R717), propane (R290), propylene (R1270), R23, R12, R134a, R404A and butane (R600) is being used on high temperature side and CO_2 on low temperature side. These natural refrigerants have zero ozone depleting potential and the majority of them have negligible global warming potential.

Use of hydrocarbons such as propylene, propane, butane, isobutane, ethane as refrigerant in subcritical cascade high temperature, HT circuit may be a serious concern due to its high flammability at a temperature of about 60 °C. Because as per the ASHRAE Standard 34 safety rating of all the above hydrocarbons is A3, which shows higher flammability if LFL or $ETFL_{60} \leqslant 100$ g/m^3 or heat of combustion (HOC) $\geqslant 19$ MJ/kg at 60 °C. The use of propylene as a refrigerant in the low temperature, LT, circuit of the transcritical cascade system will prevent the ignition due to lower operating temperature. Use of CO_2 in the LT circuit of subcritical cycle limits the evaporator temperature to the triple point of CO_2 (i.e. −56.6 °C). The applications requiring cooling temperature under −56.6 °C are not possible with the subcritical cascade system. This issue can also be resolved by using transcritical system with CO_2 in HT circuit and propylene (triple point temperature of −185.2 °C) in LT circuit. Propylene has excellent thermodynamic properties, quite similar to those of ammonia. The molar mass of 42 is ideal for turbo compressors and is only about one third of its halocarbon competitors. Propylene is cheaply and universally available. The NH_3–CO_2 cascade system employing CO_2 in the LT side and NH_3

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Nomenclature

H	specific enthalpy (kJ kg^{-1})	COP	coefficient of performance
$\dot{m}_H$	mass flow rate of CO_2(kg s^{-1})	$\dot{m}_L$	mass flow rate of propylene (kg s^{-1})
$\dot{W}_{HT}$	HT compressor power (kW)	$\dot{W}_{LT}$	LT compressor power (kW)
T	temperature (K)	η_c	compressor isentropic efficiency
E	effectiveness of internal heat exchanger	s	entropy
IT	intermediate temperature	7–12	points of refrigerant (LT side)
1–6	points of refrigerant (HT side)	sys	system
C	carbon dioxide	H	heating
P	pressure	LT	low temperature cycle
L	cooling	max	maximum
HT	high temperature cycle	prop	propylene
opt	optimum		
Q	heat transfer rate (kW)		

in the HT side is not suitable for high temperature heating applications. Sarkar et al. [23] have proposed NH_3–CO_2 cascade system with CO_2 in the HT side for simultaneous cooling and heating applications. In 2000, a new refrigeration technology to build cascade systems with carbon dioxide and propane as refrigerants was implemented in a small supermarket in Denmark. In present work, carbon dioxide–propylene cascade system with CO_2 in the HT side and C_3H_6 in the LT side has been studied. This system can offer a much larger temperature lift.

A suitable selection of refrigerants in HT and LT cycles of the transcritical cascade system can provide a large temperature lift with better system efficiency. A carbon dioxide–propane cascade system with CO_2 in the HT side and C_3H_8 in the LT side can offer a much larger temperature lift than the transcritical cycle proposed by Sarkar et al. [23] employing CO_2 in the HT side and NH_3 in the LT side. Physical properties of some of the refrigerants are presented in Table 1. In the transcritical cascade cycle, gas cooler (HT heat exchanger) pressure and temperature are independent of each other unlike the subcritical two-phase region. The high CO_2 vapor pressure in the gas cooler leads not only to a lower pressure ratio in compressor but also improves compressor efficiency, along with high heat-transfer coefficients and lower relative pressure losses. This also results in higher gas cooler temperatures with reasonable compressor power consumption. Therefore, the application of CO_2 in transcritical heat pumps for water heating up to 90 °C can be an excellent option. The main drawback of carbon dioxide as a refrigerant is its inherent high working pressure, which is much higher than that of other natural and synthetic refrigerants. Since carbon dioxide offers a much higher volumetric capacity, the problem of higher working pressure can be overcome by using optimal design involving compact and stronger components.

Vélez et al. [8] reported the results obtained on a carbon dioxide transcritical power cycle using an energy and exergy analysis. They demonstrated the viability of implementing this process as alternative energy, because of the possibility to recover energy from waste heat from industrial processes. Fartaj et al. [7] conducted a second law of thermodynamic analysis on the entire CO_2 refrigeration cycle so that the effectiveness of the components of the system can be deduced and ranked, allowing future efforts to focus on improving the components that have the highest potential for advancement. Ge and Tassou [9] established the optimal high side pressure in the transcritical cycle and derived it as a function of three important parameters consisting of ambient air temperature, the effectiveness of suction line heat exchanger and compressor efficiency.

A comparison of cascade system COP using subcritical or transcritical cycle with different combinations of refrigerants under different operating conditions as reported by the researchers in the literature with the transcritical cascade system using CO_2–propylene is presented in Table 2. It is observed that COP_{sys} in transcritical cycle with CO_2–propylene operating under the same conditions is higher than subcritical cascade cycle due to the utilization of heat rejected at the gas cooler.

Lee et al. [18] analyzed carbon dioxide–ammonia (R744–R717) subcritical cascade system thermodynamically to determine the optimum condensing temperature of CO_2 in the low temperature circuit. Bansal and Jain [1] evaluated the optimum cascade condensing temperature of CO_2 when different refrigerants such as NH_3, propane, propylene and ethanol are used in the high temperature circuits of a subcritical cascade system. Dopazo et al. [5] presented a theoretical analysis of the subcritical cascade refrigeration system with CO_2–NH_3 considering the influence of design and operating conditions on the COP of the system. Compressor efficiency was also considered in the analysis. Bingming et al. [4] reported experimental data obtained from a subcritical cascade refrigeration system with CO_2–NH_3 using screw compressors. Dopazo and Seara [6] experimentally investigated a subcritical cascade refrigeration system with CO_2/NH_3.

Kilicarslan and Hosoz [16] performed an energy and irreversibility analysis of a cascade refrigeration system employing various refrigerant couples using a computer code developed for this aim. Jain et al. [13] presented a thermodynamic model for cascaded

Table 1
Physical properties of refrigerants [11,22].

	R290	R1270	R170	R134a	R-23	R744A	R404A
Environmental classification	HC	HO	HC	HFC	HFC	–	HFC
Molecular weight	44	42	30	102	70	44	97.6
Normal boiling point (°C)	−42.1	−47.7	−88.8	−26.07	−82.1	−88.47	−46.2
Critical pressure (bars)	42.56	46	48.9	40.59	48.3	72.45	37.3
Critical temperature (°C)	96.8	94.4	32.2	101	25.6	36.37	72
Triple point (°C)	−187.6	−185.2	−183	−96.6	−155	−90.82	−73
Ozone depletion potential (ODP)	0	0	0	0	0	0.017	0
Global warming potential (GWP)	3	<0	20	1430	12,000	268	3921
ASHRAE std 34 safety rating	A3	A3	A3	A1	A1	A1	A1

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