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Theoretical analysis of a CO_2–NH_3 cascade refrigeration system for cooling applications at low temperatures

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ABSTRACT

As a result of environmental problems related to global warming and depletion of the ozone layer caused by the use of synthetic refrigerants (CFC's, HCFC's and HFC's) experienced over the last decades, the return to the use of natural substances for refrigeration purposes, appears to be the best long-term alternative. In this paper, a cascade refrigeration system with CO_2 and NH_3 as working fluids in the low and high temperature stages, respectively, has been analysed. Results of COP and exergetic efficiency versus operating and design parameters have been obtained. In addition, an optimization study based on the optimum CO_2 condensing temperature has been done. Results show that following both method's exergy analysis and energy optimization, an optimum value of condensing CO_2 temperature is obtained. The compressor isentropic efficiency influence on the optimum system COP has been demonstrated. A methodology to obtain relevant diagrams and correlations to serve as a guideline for design and optimization of this type of systems has been developed and it is presented in the paper.

1. Introduction

As a result of environmental problems related to global warming and depletion of the ozone layer caused by the use of synthetic refrigerants (CFC's, HCFC's and HFC's) experienced over the last decades, the return to the use of natural substances for refrigeration purposes appears to be sound practice. It would be a better solution to use existing and environmentally harmless natural substances as alternative refrigerants in refrigeration systems.

Amongst the natural refrigerants, Lorentzen and Petterson [1] suggested the use of carbon dioxide (CO_2) and seems to be the most promising one especially as the natural refrigerant [1–6]. The key advantages of CO_2 include the fact that is not explosive, non-toxic, easily available, environmental friendly and has excellent thermo-physical properties.

On the other hand, researches in Norway in 1993 showed that the refrigerant leakages coming from the commercial sector were 30% of the annual total [7]. In this research, the use of a cascade system using CO_2 in the low temperature stage and NH_3 in the high temperature stage turned out to be an excellent alternative for cooling applications at very low temperatures [8–10]. Researches from Eggen and Aflekt [11], Pearson and Cable [12] and Van Riessen [13] show practical examples of the use of a cascade system of CO_2/NH_3 for cooling in supermarkets. Eggen and Aflekt [11] developed research based on a prototype of a cooling system built in Norway. Pearson and Cable [12] showed data from a cooling system used in a Scottish supermarket line (ASDA) and Van Riessen [13] carried out technical energy and economic research of a cooling system used in a Dutch supermarket.

In the same way, different researchers about the performance of different cooling systems involving CO_2 have been carried out together with its reuse as a refrigerant fluid. Lorentzen and Petterson [1] evaluated the possibility of the use of a heat exchanger in a CO_2 transcritical system. Hwang et al. [6] showed experimental results and simulation research including expansors and double stage cycles. Groll et al. [14] carried out a numerical analysis of a double stage cycle changing the compression ratio of each compression stage. Bhattacharyya et al. [15] showed an optimization research of the CO_2/C_3H_8 cascade system for cooling and heating. Kim et al. [16] summed up the improvements in the performance of systems based in CO_2 and their applications. They provided a critical review of literature and discussed important trends and characteristics in the development of CO_2 technology in refrigeration applications.

Recently, studies including a wide range of possibilities in the use of CO_2 as refrigerant have been published. Deng et al. [17] described a theoretical analysis of a transcritical CO_2 ejector expansion refrigeration cycle, using an ejector as the main expansion device instead of an expansion valve. Youngming et al. [18] constructed and tested a wet-compression absorption carbon dioxide refrigeration system. Fernández-Seara et al. [19] analysed a compression–absorption cascade refrigeration system considering CO_2 and NH_3 as refrigerants in the compression stage and the pair NH_3–H_2O in the absorption stage and evaluated the possibilities of powering the cascade refrigeration system by means of a

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Nomenclature

A	area (m^2)
COP	coefficient of performance
DT	temperature difference in the cascade heat exchanger (K)
h	specific enthalpy ($kJ\,kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
RC	compressor pressure ratio (discharge/suction)
T	temperature (K)
U	overall heat transfer coefficient ($kW\,m^{-2}\,K^{-1}$)
$\dot{W}$	power (kW)
$\dot{X}$	exergy lost rate (kW)

Greeks symbols

η	efficiency
η_{II}	exergetic efficiency
ψ	stream specific exergy ($kJ\,kg^{-1}$)

Subscripts

Act	Actual
CHE	cascade heat exchanger
CO_2	carbon dioxide
Comp	compressor
Cond	condenser, condensation
Elec	electrical
Evap	evaporator, evaporation
Exp	expansion device
F	cooling space
Max	maximum
Mec	mechanical
NH_3	ammonia
Opt	optimum
Rev	reversible
s	isentropic
0	ambient

cogeneration system. Lee et al. [20] carried out a thermodynamic analysis of optimal condensing temperature of cascade–condenser in CO_2/NH_3 cascade refrigeration systems. In this work, effects of isentropic compressors efficiencies and practical limit of the compressors discharge temperatures were not taken into account and the exergetic efficiency was not evaluated.

The scope of the present research is focused on the analysis of the parameters of design and operation of a CO_2/NH_3 cascade cooling system and its influence over the system's COP and exergetic efficiency. The statistical significance of each of the parameters evaluated has been analysed. Moreover, optimization research of these parameters has been included in order to show highest COP. Finally, a discussion about the effect of the compressors' isentropic efficiency on the optimum system COP is presented.

2. System description

A schematic diagram of the cascade system is shown in Fig. 1. The cascade refrigeration system is constituted by two single stage systems connected by a heat exchanger (cascade heat exchanger). The low temperature system with CO_2 as refrigerant is used for cooling. The high temperature system with NH_3 as refrigerant is used to condensate the CO_2 of the low temperature system.

In the evaporator, the CO_2 at the evaporating temperature absorbs the cooling duty $\dot{Q}_{Evap\,CO_2}$ from the cooling space (at T_F temperature), then is compressed in the CO_2 compressor and condensed in the cascade heat exchanger at a condensing temperature of $T_{Cond\,CO_2}$, and then sent to the expansor from which the evaporator is supplied.

In the condenser, the heat flow $\dot{Q}_{Cond\,NH_3}$ is removed from the NH_3 at condensing temperature of $T_{Cond\,NH_3}$ to condensing medium (at T_0 temperature). The NH_3 is expanded, then evaporated at an evaporating temperature of $T_{Evap\,NH_3}$ in the cascade heat exchanger, and then compressed in the NH_3 compressor and discharged into the condenser.

Fig. 2 shows the process evolutions for both the CO_2 and NH_3 cycles in a log P–h diagram. Saturation lines are included.

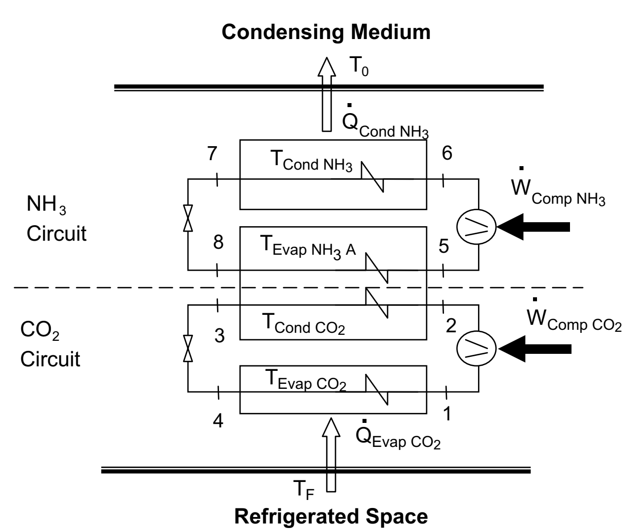

Fig. 1. Schematic diagram of the CO_2/NH_3 cascade refrigeration system.

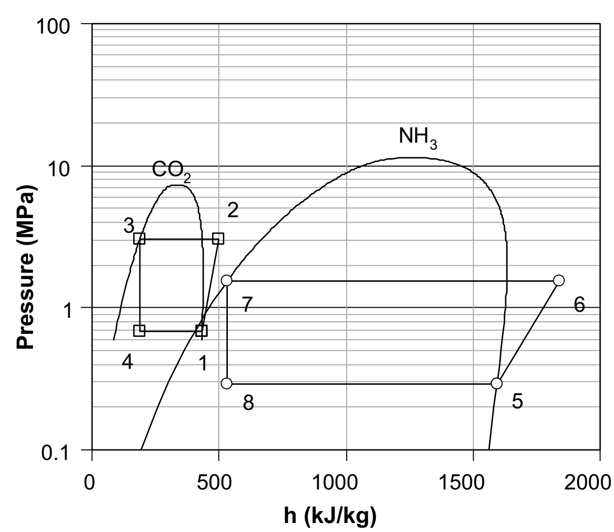

Fig. 2. Log P–h diagram of the CO_2 and the NH_3 thermodynamic cycles.