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Thermodynamic analysis of optimal condensing temperature of cascade-condenser in CO_2/NH_3 cascade refrigeration systems

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Abstract

This study thermodynamically analyzed a cascade refrigeration system that uses carbon dioxide and ammonia as refrigerants, to determine the optimal condensing temperature of the cascade-condenser given various design parameters, to maximize the COP and minimize the exergy destruction of the system. The design parameters include: the evaporating temperature, the condensing temperature and the temperature difference in the cascade-condenser. The results agreed closely with the reported experimental data. The optimal condensing temperature of the cascade-condenser increases with T_C, T_E and ΔT. The maximum COP increases with T_E, but decreases as T_C or ΔT increases. Two useful correlations that yield the optimal condensing temperature of the cascade-condenser and the corresponding maximum COP are presented.

Keywords: Refrigeration system; Compression system; Cascade system; Ammonia; Carbon dioxide; Optimization; Temperature; Condensation; COP

Etude sur la température de condensation optimale des systèmes frigorifiques au CO_2/NH_3 en cascade

Mots clés : Système frigorifique ; Système à compression ; Système en cascade ; Ammoniac ; Dioxyde de carbone ; Optimisation ; Température ; Condensation ; COP

1. Introduction

In low-temperature applications, including rapid freezing and the storage of frozen food, the required evaporating temperature of the refrigeration system ranges from −40 °C to −55 °C, so a single-stage vapor-compression refrigeration system is insufficient. Instead, two-stage or cascade refrigeration systems are used for low-temperature applications. The

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Nomenclature

COP	coefficient of performance
HTC	high-temperature circuit
h	specific enthalpy (kJ kg^{-1})
LTC	low-temperature circuit
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (MPa)
$\dot{Q}$	heat transfer rate (kW)
R^2	explained fraction of variance defined by Eq. (17)
RMSE	root-mean-square-error defined by Eq. (18)
R-RMSE	relative root-mean-square-error defined by Eq. (19)
$\dot{S}_{gen}$	entropy generation (kW K^{-1})
s	specific entropy [kJ (kg K)$^{-1}$]
T	temperature (°C or K)
t	time (s)
v	specific volume (m^3 kg^{-1})
$\dot{W}$	work (kW)
$\dot{X}_{des}$	rate of exergy destruction (kW)
x	specific exergy (kJ kg^{-1})
y	represents the value of COP$_{max}$ or $T_{MC,OPT}$

Subscripts

0	ambient
C	condenser
E	evaporator
H	high-temperature circuit
L	low-temperature circuit
MC	condensing temperature of LTC
ME	evaporating temperature of HTC
max	maximum
is	isentropic

Greek Symbol

η_s	isentropic efficiency
η_v	volumetric efficiency
ψ	stream exergy, (kJ kg^{-1})

high- and low-pressure sides of a two-stage refrigeration system are charged with the same refrigerant, whereas the high- and low-temperature circuits in a cascade system are filled separately with appropriate refrigerants. With respect to global environmental protection, the use of natural refrigerant in refrigeration systems has been demonstrated to be a complete solution to permanent alternative fluorocarbon-based refrigerant [1,2]. Therefore, using natural refrigerants in both two-stage and cascade refrigeration system helps to satisfy the obligations of environmental treaties.

Ammonia (R717) is a natural refrigerant that is most commonly adopted in low-temperature two-stage refrigeration systems, but it has disadvantages. For instance, ammonia has a pungent smell; it is toxic and moderately flammable, and has relatively large swept volume requirements at under −35 °C [3]. Additionally, the evaporating pressure of an ammonia system is below atmospheric pressure when the evaporating temperature is below −35 °C, causing air to leak into the refrigeration system, leading to short-term inefficiency and the long-term unreliability of the system. Hence, a non-toxic, non-flammable and dense refrigerant gas with a positive evaporating pressure should be chosen for evaporation below −35 °C. A cascade refrigeration system with natural refrigerants CO_2 and NH_3 meets these requirements.

A CO_2/NH_3 cascade refrigeration system uses ammonia and carbon dioxide as refrigerants in high- and low-temperature circuits, respectively. Carbon dioxide (R744) was a commonly used natural refrigerant in vapor-compression refrigeration systems for over 130 years, but it has only been fully exploited during the last decade [1,4]. Some of the characteristics of CO_2 make it a good alternative to ammonia for use in large-scale refrigeration plants operated at low temperatures. The most obvious advantages of carbon dioxide are that it is non-toxic, incombustible and has no odor. Moreover, as compared with ammonia two-stage refrigeration system, the CO_2/NH_3 cascade refrigeration system has a significantly lower charge amount of ammonia, and the COP of the cascade system exceeds that of a two-stage system at low temperatures [3,5,7]. Therefore, many investigations of the CO_2/NH_3 cascade refrigeration system are attracting attention [3,6–10].

In the design phase of a CO_2/NH_3 cascade refrigeration system, an important issue is the means of determining the optimal condensing temperature of a cascade-condenser under particular design conditions, such as condensing temperature, evaporating temperature and the temperature difference between the high- and low-circuits in cascade-condenser. Studies that seek to find the optimal condensing temperature of the CO_2/NH_3 cascade refrigeration system are lacking [8,9]. Lee et al. [9] found that the optimal condensing temperature of a cascade-condenser is −18 °C at a condensing temperature of 35 °C and an evaporating temperature of −50 °C. However, they reported only one specific condition and did not evaluate the effects of varying the design conditions, such as the condensing and evaporating temperatures, on the optimal condensing temperature of the cascade-condenser and its corresponding maximum COP. Additionally, Lee's compressor model [9] took into account only a constant isentropic efficiency and did not vary by the pressure ratio. In that case, Lee's results differ greatly from the real case.

Hence, this work employs thermodynamic energy and exergy analysis to determine the optimal condensing temperature of the cascade-condenser in a low-temperature CO_2/NH_3 cascade refrigeration system for various values of the design parameters, such as the condensing temperature, the