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Natural refrigerant-based subcritical and transcritical cycles for high temperature heating

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Abstract

Theoretical analyses of subcritical/transcritical heat pumps using four natural refrigerants, carbon dioxide, ammonia, propane and isobutane have been carried out for high temperature heating applications at different heating outlet temperatures and heat sources using computer models. The compressor discharge pressures have been optimized for transcritical and subcritical (with near critical operation of condenser) cycles. Results show that for subcritical heat pumps, use of subcooling is efficient for heating applications with a gliding temperature. Results also show that although propane yields better coefficient of performance (COP) in low temperature heating applications, ammonia performs the best in high temperature heating applications. Finally, design aspects of major components of all the four heat pumps for high temperature heating have been discussed, particularly with reference to suitability of available lubricants to the newly evolved operating conditions.

Keywords: Heat pump; Carbon dioxide; Ammonia; Propane; Isobutane; Research; Thermodynamic cycle; Transcritical cycle; Performance; COP

Cycles souscritiques et transcritiques utilisant des frigorigènes naturels dans les applications à température élevée

Mots clés : Pompe à chaleur ; Dioxyde de carbone ; Ammoniac ; Propane ; Isobutane ; Recherche ; Cycle thermodynamique ; Cycle transcritique ; Performance ; COP

1. Introduction

In the last few decades, several studies have been carried out to find suitable refrigerants for heat pumps applicable to high temperature heating. Previously, R115 was used for high temperature process heat applications, but due to its negative impact on the environment, researchers have proposed various alternative synthetic refrigerants of zero ODP such as R143, R152, E143 and E245 [1]. However, these refrigerants have higher GWP. Hence, environmentally benign natural refrigerants such as carbon dioxide, ammonia, propane, butane, isobutane and propylene [2] appear to be better alternatives for heat pump applications. Ammonia is a very old refrigerant, which is generally used up to a temperature of about 70 °C. Carbon dioxide has been revived as a potential refrigerant for heat pump applications,

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Nomenclature

AT	temperature approach (K)
COP	coefficient of performance
f	friction factor
h	specific enthalpy (kJ kg^{-1})
Nu_0	Nusselt number at bulk property
P	pressure (MPa)
Pr	Prandtl number
R_c	compressor pressure ratio
Re	Reynolds number
t	temperature (°C)
V_c	volumetric capacity (MJ/m^3)

Subscripts

1–6	state points of refrigerant
c	refrigerant outlet in condenser/gas cooler
ci	fluid inlet to condenser/gas cooler
co	fluid outlet from condenser/gas cooler
crit	critical property
dis	compressor discharge
e	evaporator
opt	optimum
sv	saturated vapour

which can be used up to 120 °C [3]. Although most of the common process heat applications in pulp, paper, chemical, plastics, agricultural, textile, plaster and food industries require heating up to 140 °C [1], some food drying and petrochemical processes require temperatures above 200 °C. Because no such heat pump system is available for these high temperature heating applications, electrical heater or heat transformer is used in these applications (e.g. in milk powder production, air is heated up to 70–80 °C by a heat pump and then by an electrical heater up to the required temperature), which yields a COP less than or equal to 1.0. In this study subcritical and transcritical heat pumps using four natural refrigerants, ammonia, carbon dioxide, propane and isobutane have been proposed for high temperature heating applications. Barring a few individual deficiencies, such as toxicity and flammability of ammonia, flammability of hydrocarbons, and high pressure and low theoretical COP of CO_2, these natural refrigerants offer various advantages when compared to synthetic refrigerants. Even though the theoretical COP of a simple CO_2 cycle is relatively low, the COP of an actual CO_2 system could be considerably higher due to high compressor efficiency and excellent transport properties of CO_2. During the last few years there have been many studies, which show that the COP of a real CO_2 cycle is higher than that of cycles using conventional working fluids. This indicates that actual system's COP depends very much on component and system design. However, this aspect cannot be revealed in a relatively simple theoretical study such as the one presented in this paper.

In the present study, the compressor discharge pressure of transcritical cycles have been optimized and then performance analyses of heat pumps based on four natural refrigerants (carbon dioxide, ammonia, propane and isobutane) have been carried out for heating applications at different heating outlet temperatures. Two heat sources: a low temperature source (e.g. ambient air or ground water) and a high temperature source (e.g. power plant condenser) have been considered for the analyses. Finally, design related issues of the major components of all the four refrigerants based heat pumps for high temperature heating have been discussed with a special reference to whether currently available lubricants would be suitable for use in the new systems having difficult operating conditions.

2. Optimum discharge pressures

Performance analyses of a carbon dioxide based transcritical cycle showed that there exists an optimum compressor discharge pressure, where the cycle yields the maximum COP. The optimum pressure depends on evaporation temperature, cooler exit temperature, internal heat exchanger effectiveness and compressor isentropic efficiency. However, the effect of the last two parameters is found to be negligible compared to others [4]. Similar behaviour can be observed for other refrigerant-based transcritical cycles also. It is very interesting to note that subcritical cycles also yield optimum discharge pressure when the condenser is operated near the critical point (Table 1). For the subcritical cycles, if the temperature of the refrigerant at condenser exit is in subcooled region, an optimum condensation pressure is found to exist, which yields maximum COP. Fig. 1 shows the P–h diagram with several constant temperature lines. Due to the curvy nature of the isotherms in the super-critical region, such cycles tend to have an optimum gas cooler pressure [4]. If we lower the gas cooler exit temperature in subcooled region, this nature of the isotherms may continue up to some extent and the existence of optimum condensation pressure is observed; however, eventually the isotherms become vertical and there is no optimum point in the subcooled region. In that case, the saturated liquid point becomes the optimum. Thus, to

Table 1
Critical properties of natural refrigerants studied

Refrigerant	Carbon dioxide	Ammonia	Propane	Isobutane
t_{crit} (°C)	31.06	132.25	96.70	134.70
P_{crit} (MPa)	7.377	11.33	4.248	3.640