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Simulation of a transcritical CO_2 heat pump cycle for simultaneous cooling and heating applications

J. Sarkar, Souvik Bhattacharyya*, M. Ram Gopal

Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India

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Abstract

A steady state simulation model has been developed to evaluate the system performance of a transcritical carbon dioxide heat pump for simultaneous heating and cooling. The simulated results are found to be in reasonable agreement with experimental results reported in the literature. Such a system is suitable, for example, in dairy plants where simultaneous cooling at 4 °C and heating at 73 °C are required. The optimal COP was found to be a function of the compressor speed, the coolant inlet temperature to the evaporator and inlet temperature of the fluid to be heated in the gas cooler and compressor discharge pressure. An optimizing study for the best allocation of the fixed total heat exchanger inventory between the evaporator and the gas cooler based on the heat exchanger area has been carried out. Effect of heat transfer in the heat exchangers on system performance has been presented as well. Finally, a novel nomogram has been developed and it is expected to offer useful guidelines for system design and its optimisation.
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Keywords: Research; Experiment; Growth; Crystal; Frost; Defrosting; Modelling; Plate; Electric field; Alternating current

Elimination des cristaux de givre sur une plaque froide: effets des fréquences stationnaires et de balayage des champs électriques

Mots clés : Recherche ; Expérimentation ; Croissance ; Cristal ; Givre ; Dégivrage ; Modélisation ; Plaque ; Champ électrique ; Courant alternatif

1. Introduction

A carbon dioxide based vapour compression refrigeration system was patented in 1850, followed by several decades of its use. However, due to problems arising from its very low critical temperature and high operating pressure, carbon dioxide as a refrigerant was slowly replaced by the synthetic halocarbon refrigerants. Interestingly though, with the discovery of the harmful effects of the synthetic refrigerants on environment, there is a renewed interest in natural refrigerants such as carbon dioxide. Lorentzen [1] through his seminal studies has shown that the problem of low critical temperature of carbon dioxide can be effectively overcome by operating the system in the transcritical region. This has led to the development of transcritical carbon dioxide cycles where

* Corresponding author. Tel.: +91 3222 282904; fax: +91 3222 255303.
E-mail address: souvik@mech.iitkgp.ernet.in (S. Bhattacharyya).

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
d	inner tube diameter (m)
D	outer tube diameter (m)
G	mass velocity ($kg\ m^{-2}\ s^{-1}$)
h	specific enthalpy ($kJ\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_W	wall thermal conductivity ($W\ m^{-1}\ K^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
N	compressor speed (rpm)
Nu	Nusselt number
P	pressure (bar)
Pr	Prandtl number
Q	heat transfer (W)
Re	Reynolds number
T, t	temperatures, K and °C
UA	overall heat transfer coefficient area of heat transfer product ($W\ K^{-1}$)
V_s	swept volume of compressor (m^3)
x	quality of saturated carbon dioxide liquid vapor mixture

Greek symbols

ρ	density ($kg\ m^{-3}$)
μ	dynamic viscosity ($N\ m^{-2}\ s$)
ΔL	length segment (m)
α	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
f, ξ	friction factor

Subscripts

1–6	state point of refrigerant
dis	compressor discharge
ev	evaporator
evr	refrigerant in evaporator
evw	evaporator water
gc	gas cooler
gcr	gas cooler refrigerant
i	inner
l	liquid
o	outer
opt	optimum
ref/r	refrigerant
rb	refrigerant at bulk temperature
rw	refrigerant at wall temperature
suc	suction
w	water
wi	water inlet

Superscripts

i	segmental step

the condenser gets replaced by a gas cooler. It was found that the use of a gas cooler with heat rejection taking place over an unusually large temperature glide offers several unique possibilities such as simultaneous refrigeration and hot water heating/steam production, simpler control of capacity, etc. Several theoretical and experimental studies have spurred further interest in carbon dioxide based systems in varied applications. Extensive applications of carbon dioxide heat pumps were reported by Neksa [2]. Yarrall et al. [3] have carried out experimental studies on a transcritical carbon dioxide heat pump prototype. Environment friendliness, low price, easy availability, non-flammability, non-toxicity, compatibility with various common materials, compactness due to high operating pressures, excellent transport properties are cited as some of the reasons behind the revival of carbon dioxide as a refrigerant.

Carbon dioxide based systems have strong potential in two sectors (i) mobile air-conditioning [4], and (ii) heat pumps for simultaneous cooling and heating. Several research groups have undertaken sustained studies over the last decade and CO_2 heat pump based water heaters have been launched in Japan lately. Due to its transcritical nature, the performance of carbon dioxide system will not be exactly the same as the conventional subcritical vapour compression refrigeration and heat pump systems. Hence, simulation models developed for the conventional systems cannot be employed for this new system. But, there is a need for theoretical system simulation studies as experimental performance evaluation is difficult, expensive and time consuming. So, accurate computer simulation of the system to predict its steady state performance and effects of various design and operating parameters on the steady state performance will be very useful. In the present study, the simulation results of a transcritical carbon dioxide heat pump system for dairy applications have been presented; in such systems simultaneous cooling and heating at 4 and 73 °C, respectively, is required. Although, the several simulation studies of conventional vapour compression system have been reported [5–7], such studies for transcritical CO_2 based systems are limited in number and scope. A CO_2 based air-conditioning system was simulated by Byon et al. [8] employing assumed UA values for the heat exchangers; however, due to large variation in CO_2 properties in the heat exchanger and because of the transcritical nature of the cycle this rather simplifying assumption renders the model less realistic. Pfafferott et al. [9] reported simulation of CO_2 refrigeration system incorporating cross flow heat exchangers with air as secondary fluid. Ortiz et al. [10] carried out CO_2 system simulation to evaluate the performance of air-to-air air-conditioners and heat pumps. Heat exchangers were cross

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