available at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/ijrefrig

Effect of PAG-type lubricating oil on heat transfer characteristics of supercritical carbon dioxide cooled inside a small internally grooved tube

*Chaobin Dang**, *Koji Iino*, *Eiji Hihara*

Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, The University of Tokyo, Kashiwanoha 5-1-5, Kashiwa-shi, Chiba 277-8563, Japan

ARTICLE INFO

Article history:
Received 11 March 2009
Received in revised form
4 December 2009
Accepted 11 December 2009
Available online 23 December 2009

Keywords:
Carbon dioxide
Transcritical cycle
Experiment
Heat transfer
Parameter
Oil
Polyalkylene glycol
Pressure drop

ABSTRACT

Heat transfer characteristics of supercritical CO_2 cooled inside a small internally grooved tube were investigated. The mean inner diameter (ID) and helix angle of this tube were 2 mm and 6.3°, respectively. Experiments were conducted in the pressure range of 8–10 MPa and mass flux range of 400–1200 kg m^{-2} s^{-1}. The effect of PAG-type lubricating oil on the heat transfer characteristics was investigated by changing the oil concentration from 0% to 5%. The drop in the heat transfer coefficient was 30–50% and 50–70% at oil concentrations of 1% and 3%, respectively. The heat transfer coefficient of CO_2 in the grooved tube was higher than that in the smooth tube at all oil concentrations tested. The experimental results indicated that the grooved tube has a large heat transfer area and facilitates the breaking up of the oil film.

Effet de l'huile lubrifiante de type PAG sur les caractéristiques du transfert de chaleur du dioxyde de carbone supercritique refroidi à l'intérieur d'un petit tube rainuré du côté interne

Mots clés : Dioxyde de carbone ; Cycle transcritique ; Expérimentation ; Transfert de chaleur ; Paramètre ; Huile ; Polyalkylène glycol ; Chute de pression

* *Corresponding author*. Tel./fax: +81 47 136 4647.
E-mail address: dangcb@k.u-tokyo.ac.jp (C. Dang).
0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2009.12.010

Nomenclature

A	heat transfer area, [m^2]
$\bar{c}_p$	integrated specific heat, [$J\,kg^{-1}\,K^{-1}$] (($(h_b/h_w)/(T_b/T_w)$))
ΔP	pressure drop, [MPa]
f	friction factor
h	specific enthalpy, [$J\,kg^{-1}$]
$LMTD_w$	logarithmic mean temperature difference between refrigerant and wall of tube, [°C]
Nu	Nusselt number, ($\alpha d/k$)
Pr	Prandtl number, ($\mu c_p/k$)
Re	Reynolds number, (Gd/μ)
T	temperature, [°C]
c_p	specific heat at constant pressure, [$J\,kg^{-1}\,K^{-1}$]
d	diameter, [m]
ΔT	temperature difference, [°C]
G	mass flux, [$kg\,m^{-2}\,s^{-1}$]
k	thermal conductivity, [$W\,m^{-1}\,K^{-1}$]
m	mass flow rate, [$kg\,s^{-1}$]
P	pressure, [MPa]
Q	heat flux, [$W\,m^{-2}$]
W	weight, [g]
x	oil concentration, [wt%]

Greek symbols

μ	dynamic viscosity, [$kg\,m^{-1}\,s^{-1}$]
α	heat transfer coefficient, [$W\,m^{-2}\,K^{-1}$]
β	helix angle, [°]
η	area enlargement ratio

Subscripts

1	inlet
b	bulk
gr	grooved tube
sm	smooth tube
water	water
2	outlet
f	film
m	pseudocritical
w	wall

1. Introduction

After the commercialization of “EcoCute” in 2001, there has been a steady increase in the shipment of CO_2 heat pump water heater. The total domestic shipment volume reached 2 million units by the end of October 2009, and the government expects this volume to increase to 10 million units by 2020 (http://www.jraia.or.jp/frameset_product.html). The coefficient of performance (COP) of the heat pump units increased from 3.46 in 2001 to 4.90 towards the end of 2007 (survey results by TEPCO, http://www.enecho.meti.go.jp/info/committee/0709203/4.pdf). This improvement in the COP is attributed to the improvement in the efficiency of the components of the heat pump unit, including the compressor and heat exchangers.

Considerable research has been carried out on applying internally grooved tubes to evaporation and condensation processes. As a result of the continual improvements made to the tube design over the past three decades, the evaporation and condensation heat transfer coefficients in these tubes have increased fourfold and twofold, respectively (Sasaki, 2006). However, very few studies have been carried out on the heat transfer characteristics of supercritical fluids cooled inside grooved tubes. The only study on the heat transfer of supercritical CO_2 has been carried out by Koyama et al. (2006); they compared the heat transfer coefficient (α) of CO_2 cooled inside a smooth tube and that of CO_2 cooled in two microfin tubes having an inner diameter (ID) of 6 mm, a helix angle (β) of 24°, and an area enlargement ratio (η) of 1.4. They concluded that α for the microfin tube is approximately 2.4 times that for the smooth tube.

The α values of supercritical CO_2 and CO_2 entrained with a PAG-type lubricating oil and cooled inside smooth tubes (diameter: 1–6 mm) have been systematically investigated at our institute (Dang and Hihara, 2004a,b; Dang et al., 2007, 2008). Yun et al. (2007) investigated the effect of the presence of PAG-type oil on α and the pressure drop (ΔP) for supercritical CO_2 cooled in a minichannel tube with a hydraulic diameter of 1.0 mm. When the oil concentration (x) was increased from 0% to 4%, α decreased by up to 20.4%, while ΔP increased by 4.8 times. Recently, Cheng et al. (2008) published a review on the cooling heat transfer of supercritical CO_2 in macro- and microchannels and summarized the heat transfer characteristics of pure CO_2 and the effect of addition of lubricating oils. Although these previous researches have investigated the heat transfer characteristics of supercritical CO_2 cooled inside microchannels and discussed the effect of the presence of a lubricating oil, they have not focused on internally grooved tubes, which are required for designing high-performance, compact systems.

The purpose of this study is to experimentally investigate the heat transfer characteristics of supercritical CO_2 cooled inside a small internally grooved tube in the presence and absence of PAG-type lubricating oil. The mean ID of the tube is approximately 2 mm, and β and η are 6.3° and 2.0, respectively. x is changed from 0% (oil-free condition) to 5%, and experiments are carried out in the pressure (P) range of 8–10 MPa and mass flux (G) range of 800–1200 $kg\,m^{-2}\,s^{-1}$. To the best of our knowledge, the grooved tube used in the present study is the smallest among those used thus far for studying the heat transfer performance of supercritical CO_2.

2. Experimental instruments

2.1. Experimental setup

In this study, the heat transfer performance of the grooved tube containing supercritical CO_2 is investigated in the presence and absence of the lubricating oil. Two test loops,