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Study on two-phase flow pattern of supercritical carbon dioxide with entrained PAG-type lubricating oil in a gas cooler

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ABSTRACT

In order to clarify the heat transfer mechanism of supercritical carbon dioxide flowing with a small amount of lubricating oil, visualization experiments were conducted using two sight glass tubes with inner diameters of 2 and 6 mm. The visualization images were recorded using a high-speed CCD camera with shutter speed changing from 500 to 10,000 pps (pictures per second). PAG-type oil, which is partially miscible with supercritical carbon dioxide, was used. The experiments were conducted with lubricating oil concentrations of 1 and 5 wt%, pressures between 8 and 10 MPa, and mass fluxes between 200 and 1200 kg m^{-2} s^{-1}.

The visualization images revealed that the two-phase flow pattern inside the gas cooler was determined by many factors, including the tube diameter, oil concentration, temperature, pressure, and mass flux. For a small size tube of 2 mm ID, the formation of both oil droplets in the bulk region and an oil film along the inner wall of the tube was confirmed. At low temperatures, a large number of oil droplets were observed flowing with CO_2 with a slip ratio of approximately 0.7. With an increase in the bulk temperature, both the dimension and number of oil droplets entrained with CO_2 decreased, and the flow of the oil film became clearly visible. For a large tube of 6 mm ID, the flow pattern at a low mass flow rate was a separated wavy flow; with an increase in mass flow, the flow pattern changed to annular flow, which corresponds to a distinct decrease in the heat transfer coefficient due to the heat resistance of oil layer. The transition of the flow pattern is considered due to the shear stress between the oil layer and bulk CO_2. In addition, the dissolution of CO_2 into PAG oil as well as the change in the solubility and thermodynamic properties of CO_2 with the temperature and pressure makes the prediction of the flow patterns a challenging task. The relationship between the flow pattern and heat transfer characteristics was also discussed.

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Etude sur la configuration de l'écoulement diphasique du dioxyde de carbone supercritique avec de l'huile lubrifiante de type PAG entraînée dans un refroidisseur à gaz

Mots clés : Dioxyde de carbone ; Cycle transcritique ; Expérimentation ; Écoulement diphasique ; Refroidisseur de gaz ; Mélange ; Huile ; Polyalkylène glycol

Nomenclature

A	heat transfer area, m^2
c_p	specific heat, $J\,kg^{-1}\,K^{-1}$
d	diameter, m
ΔT	temperature difference, °C
G	mass flux, $kg\,m^{-2}\,s^{-1}$
P	pressure, MPa
q	heat flux, $W\,m^{-2}$
T	temperature, °C
W	weight, kg
x	oil concentration, wt%

Greek symbols

α	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$

Subscripts

1	inlet
2	outlet
CO_2	CO_2
bulk	bulk
oil	oil
wall	wall
water	water

1. Introduction

In an actual heat pump cycle, lubricating oil is commonly used in the compressor for lubrication, cooling, and sealing purposes. However, small amounts of lubricating oil may be discharged by the compressor along with the refrigerant; this oil would flow through the heat exchangers and expansion devices and finally return to the compressor. Therefore, a mixture of the refrigerant and a small amount of oil, instead of pure refrigerant, flows inside the heat exchanger and exchanges heat with the environment. Due to the excellent lubricity and stability in the transcritical CO_2 environment, PAG (polyalkylene glycol) type oils are widely applied in the CO_2 heat pump cycle (Kaneko et al., 2006). It is, therefore, important to understand the heat transfer performance of supercritical CO_2 with entrained PAG-type lubricating oils.

Dang et al. (2007) have investigated the heat transfer characteristics of supercritical CO_2 with small amounts of entrained PAG oil. The experimental results showed a decrease in the heat transfer coefficient and an increase in the pressure drop with the entrainment of lubricating oil. The maximum reduction in the heat transfer coefficient was about 75%, which occurred in the vicinity of the pseudocritical temperature. In addition, the transition of the flow pattern was found to drastically affect the heat transfer performance. The changes in the thermophysical properties of supercritical CO_2 with the temperature and pressure are the main parameters used to predict the flow pattern and heat transfer performance of supercritical CO_2 with lubricating oil; moreover, a change in the solubility of CO_2 into PAG oil would only make the issue more challenging. To understand the experimental results of the heat transfer performance with oil entrainment, information concerning the flow pattern inside the gas cooler is of significant importance. However, mainly due to the difficulty in dealing with the high operation pressures, a systematic investigation of the flow pattern under wide experimental conditions is absent in the literature. The current available experimental results from open literature concerning the flow and heat transfer of supercritical CO_2 contaminated with PAG-type oil include the following: Yun et al. (2006) measured the heat transfer of supercritical CO_2 with PAG-type oil in microchannel with a diameter of 1.0 mm. The mass flux was varied from 200 to 400 $kg\,m^{-2}\,s^{-1}$ at heat flux of 20 $kW\,m^{-2}$, and the test section inlet pressures of CO_2 were changed from 8.4 to 10.4 MPa with inlet temperatures controlled from 40 to 80 °C. By comparing the measured value at different oil concentration, they concluded that the average heat transfer coefficient decreased 9% for 2 wt%, and 20.4% for 4 wt%. Gao and Honda (Gao and Honda, 2002) investigated the heat transfer characteristics of supercritical CO_2 with an oil concentration of 1% inside a 4.5 mm ID tube at a pressure of 7.7 MPa, and reported a maximum decrease of 40% in its heat transfer performance at pseudocritical temperature when compared to pure CO_2. Mori et al. (2002) observed the flow pattern of a CO_2–oil mixture inside a gas cooler with a 6 mm ID tube at a pressure of 9.5 MPa. Although the oil concentration was unknown, it was found that the oil separated from CO_2 and formed an oil layer near the inner wall. Subsequent measurements of the heat transfer coefficient revealed a decrease in heat transfer, which was explained by the heat resistance of the oil layer.