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Experimental investigation of heat transfer to supercritical R245fa flowing vertically upward in a circular tube

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ABSTRACT

The characteristics of supercritical heat transfer of organic fluid R245fa under heating conditions was investigated experimentally in a vertical tube with an inner diameter of 4 mm and a length of 1.04 m. The heat flux ranges from 15 to 100 kW/m^2 and mass flux from 400 to 800 kg/m^2 s. The experiments were conducted at pressures of 4.0, 4.5, and 5.0 MPa. The local heat transfer coefficients were determined with respect to the heat flux, mass flux, and pressure. The experimental results show that the heat transfer deteriorates abruptly at moderate heat and mass fluxes, which can be considered as mixed convection, whereas it deteriorates gradually under other working conditions, which can be considered as forced convection. The irreproducibility of the heat transfer is also demonstrated. The experimental data are compared with existing correlations and reveal that 70% of the experimental data can be predicted by Yamagata's correlation with an accuracy of ± 30%. However, the prediction accuracy under abrupt deterioration conditions needs further improvement.

1. Introduction

Recently, the utilization of low-grade heat sources in various industrial processes has attracted increasing attention to achieve energy conservation and a reduction in carbon dioxide emissions. For example, the low-grade heat source in the steel industry, which are typically below 200 °C, is one of the major targets to be exploited. Among the methods for recovering these low-grade heat sources, the organic Rankine cycle (ORC) using an organic fluid instead of water in the traditional Rankine cycle can generate electricity from the waste heat, and thus reduce the fuel usage and emission of greenhouse gases. To further increase the efficiency of an ORC system, particularly of the boiler (evaporator), researchers have developed technologies such as the application of binary working fluids for achieving a better agreement with the temperature profile of the heat source. Operating the heating process under supercritical pressure is another promising approach to increase the system efficiency because more work can be recovered. Therefore, in this view, the supercritical heat transfer characteristics of an organic fluid, such as R245fa, need to be investigated.

Supercritical heat transfer was first investigated with water (P_{cri} = 22.064 MPa, T_{cri} = 373.95 °C) mainly for supercritical water-cooled nuclear reactors. Yamagata et al. [1] investigated supercritical water flowing in both horizontal and vertical tubes under the conditions: pressure from 22.6 to 29.4 MPa, bulk temperature from 230 to 540 °C, heat flux from 116 to 930 kW/m^2, and mass flux from 310 to 1830 kg/m^2 s. The study showed that larger heat transfer coefficients were obtained near the pseudocritical point and accurately predicted by the proposed correlation at a low heat flux to mass flux ratio, whereas the heat transfer deteriorated at a high heat flux.

Compared with supercritical water, carbon dioxide (P_{cri} = 7.3773 MPa, T_{cri} = 30.978 °C) has a lower critical pressure and temperature, which makes its experimental research relatively easy. In addition, the heat transfer characteristics of carbon dioxide under supercritical pressure was required for the application of an air source heat pump, and hence, researchers have conducted a series of experiments to further investigate the characteristics of supercritical heat transfer.

Tanaka et al. [2] performed a forced convection experiment with supercritical carbon dioxide. They proposed that the heat transfer coefficient would be maximum when the pseudocritical temperature was located in the buffer zone because the temperature drop across the boundary layer was most effectively diminished. In contrast, the minimum value was suggested to be obtained when the pseudocritical temperature was located near the bottom of the turbulent core region, which would increase the thickness of the gas-like fluid layer. A series of experiments

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Nomenclature

Bu	dimensionless buoyancy parameter
d	diameter, m
G	mass flux, kg/(m^2 s)
Gr	Grashof number
h	heat transfer coefficient, W/(m^2 K)
I	imposed current on test section, A
i	enthalpy, kJ/kg
k	thermal conductivity, W/(m·K)
L	test section length, m
Nu	Nusselt number
P	pressure, MPa
q	heat flux, kW/m^2
r	radius, m
Re	Reynolds number
SD	standard deviation,%
T	temperature, °C
U	imposed voltage on test section, V

Subscripts

b	bulk properties
cri	critical point
i	inner diameter
pc	pseudocritical
v	quantities per unit volume
wi	inner wall
wo	outer wall

on the supercritical heat transfer of carbon dioxide in a vertical pipe were conducted [3–5]. The corresponding results showed that the flow in a large-diameter pipe was more susceptible to a reduction in the heat transfer because of buoyancy; however, a deterioration occurred in a small-diameter (4.4 mm) pipe. Kim et al. [6–8] experimentally investigated the supercritical carbon dioxide vertical flow with a tube inner diameter of 4.5 mm. The pressure ranged from 7.46 to 10.26 MPa, heat flux from 38 to 234 kW/m^2, and mass flux from 208 to 874 kg/m^2 s. A deterioration occurred at a moderate wall heat flux and low mass flux in the upward flow, whereas such characteristics were not found for the downward flow. The ratio of the shear stress reduction to the wall shear stress was considered owing to the flow acceleration and buoyancy effects, and a correlation based on the considerations was developed.

In addition to experiments under heating conditions, studies have also been conducted under cooling conditions to obtain the supercritical heat transfer characteristics. Liao and Zhao [9] investigated the heat transfer of supercritical carbon dioxide flowing in horizontal mini/micro circular tubes during cooling. The Nusselt number decreased with the reduction in the tube diameters under the experimental conditions, indicating that the buoyancy effect was still significant. Dang et al. [10,11] experimentally investigated the supercritical cooling characteristics of carbon dioxide and effect of lubricating oil. It was found that the heat transfer coefficient increased with increasing mass flux, whereas the effect of pressure depended on the property variation along the flow direction; the effects of heat flux and tube diameter depended on the property variation in the radial direction. The heat transfer coefficient decreased, whereas the pressure drop increased when a lubricating oil was contained.

In contrast, various geometries have been applied to reduce the heat transfer deterioration. Jiang et al. [12,13] investigated supercritical carbon dioxide in vertical tubes with diameters of 0.948 and 4 mm and in porous media with the particle diameter ranging from 0.2 to 0.28 mm. It was found that the convection heat transfer coefficients in porous tubes with low heat fluxes were much smaller than those with high heat fluxes, which differed from the heat transfer in bare mini-tubes. Licht et al. [14,15] conducted an experiment on supercritical water in circular and square annular flow channels. It was concluded that at a low mass flux, the heat transfer deteriorated at sub-pseudocritical temperatures for both the geometries. Bae et al. [16] conducted an experiment in a tube with an inserted helical wire with an outer diameter of 1.3 mm. The results yielded a value of the heat transfer coefficient that was twice of that obtained from the experiment with a plain tube of the same size near the pseudocritical temperature. It was concluded that the additional turbulence generated by the wire contributed to the increase in the heat transfer. Zhang et al. [17] and Xu et al. [18] conducted an experiment on a supercritical fluid flowing through a helically coiled tube under heating and cooling conditions, respectively; the former investigated the buoyancy effect on the vertically set and helically coiled tube, whereas the latter showed a heat transfer enhancement compared with a straight tube.

In contrast with the extensive experiments on supercritical water and carbon dioxide, the research on organic fluids is limited. Yamashita et al. [19] investigated the heat transfer and pressure drop of R22 in a vertically upward flow in a tube with diameter of 4.4 mm. It was found that the critical heat flux for the occurrence of the deterioration of heat transfer increased with smaller tube diameters. In addition, the frictional pressure drop in the near-pseudocritical region reduced as the heat flux increased. Jiang [20] conducted an experiment on R22 and ethanol, and the results showed that for supercritical R22, the frictional pressure drop increased significantly with the heat flux, and both the buoyancy and flow acceleration had a negligible effect on the heat transfer.

From the literature review, the heat transfer under supercritical pressures show different characteristics because of its significantly varied thermo-physical properties. The heat transfer coefficient has a maximum in the vicinity of pseudocritical point, and it would be deteriorated uncertain heat fluxes. The buoyancy and acceleration are believed to be the mechanism for the characteristics.

Besides, some special features such as the varied heat transfer characteristics with different inlet enthalpies [1,21] also appeared in literatures, indicating the complexity for such a heat transfer problem.

In this study, the heat transfer characteristics of R245fa (P_{cri} = 3.651 MPa, T_{cri} = 154.01 °C) under supercritical pressures in a vertically upward flow are presented. The inner diameter and length of the test tube are 4 mm and 1.04 m, respectively. To acquire better knowledge of the heat transfer characteristics, a set of complex working conditions have been designed as follows: heat flux ranges from 15 to 100 kW/m^2 and mass flux from 400 to 800 kg/m^2 s. The experiments are conducted at a pressure of 4.0, 4.5, and 5.0 MPa. The effects of the mass flux, heat flux, and pressure are discussed based on the experimental data. In addition, the proposed method is compared with the existing correlations.

2. Experimental apparatus and data deduction

Fig. 1 shows the schematic of the test facility. The working fluid is circulated using a magnetic gear pump. The mass flow rate is controlled by the rotational speed of the pump and ratio of the bypass. A Coriolis type flowmeter is used to measure the mass flow rate. A stainless-steel tube is connected after the preheater as the