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Supercritical heat transfer characteristics of R1233zd(E) in vertically upward flow

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ABSTRACT

The recently developed low-global-warming-potential working fluid R1233zd(E) is regarded as an alternative to R245fa in the organic Rankine cycle (ORC) considering the environmental impacts. In this study, the heat transfer characteristics of R1233zd(E) at supercritical pressures were investigated experimentally in a vertically upward flow inside a tube. The inner diameter and length of the test tube were 4 mm and 1.04 m, respectively. With the known supercritical heat transfer characteristics of R245fa, the experiment was conducted under the mass fluxes of 400 and 600 kg/m^2 s, heat flux from 20 to 80 kW/m^2, and pressure of 3.93 and 4.40 MPa, which were equal to the reduced pressure (P/P_{cri}) of 1.10 and 1.23, respectively. The effects of mass flux, heat flux, and pressure are discussed based on the experimental data. The experimental results are compared with existing correlations and the correlation proposed by Petukhov et al. shows the best predictability. Moreover, a comparison with the heat transfer coefficients of R245fa is presented. For the new R1233zd(E) working fluid, the abrupt deterioration characteristics did not occur under the experimental conditions, and a higher heat transfer coefficient was obtained in the supercritical region, in comparison to that obtained with R245fa.

1. Introduction

As a promising technology for low-grade heat resource recovery, power plants based on the organic Rankine cycle (ORC) have been available in the market since the 1980s. According to the survey conducted by Quoilin et al. [1], the R245fa hydrofluorocarbon (HFC) is commonly used as the working fluid in commercial ORC based power plants. With regard to environmental impacts, however, R245fa has a high-global-warming-potential (GWP) of 1030, even though its ozone depletion potential (ODP) is 0. To further minimize the emission of greenhouse gases, another global commitment called the Kigali Amendment to the Montreal Protocol was agreed in 2016. Accordingly, HFCs, such as R245fa, shall be phased down by 85% by 2036 in developed countries, and by 80% or more by 2045 in developing countries. Hydrofluoroolefin (HFO) refrigerants are categorized as having zero ODP and low GWP. Thus, they offer a more environmentally friendly alternative to CFCs, HCFCs, and HFCs. Several studies have been conducted on HFO refrigerants, such as R1234yf and R1234ze, and have been mainly concerned with the measurement of thermophysical properties, heat transfer characteristics, refrigeration cycle performance, and safety issues.

Recently, the HFO-1233zd(E) developed by Honeywell has been considered as an alternative for application in the ORC owing to its low GWP of 4. As a recently developed working fluid, a database of accurate thermophysical properties is necessary in order to use it in developing a thermal system. The measurement of the PVT behavior of vapor pressure and the speed of sound have been reported by Mondéjar et al. [2]. Other thermophysical properties, including surface tension [3], heat capacity [4], and saturated pressure [5], have also been reported.

Cycle performance with R1233zd(E) was evaluated both by simulation and experiment. The simulation results revealed that the lower saturation pressure and vapor density of R1233zd(E) could generate an 8.7% higher cycle efficiency in comparison to an equivalent R245fa based system [6]. A drop-in replacement experiment with R1233zd(E) has been conducted by Eyerer et al. [7], and the obtained results revealed that R1233zd(E) performed 6.9% better than R245fa, with respect to the maximum thermal efficiencies. This indicates that it could be used as a substitute for R245fa in existing ORC systems.

A limited number of literatures have been published with regard to the heat transfer characteristics of R1233zd(E). Nagata et al. [8] have experimentally investigated the free convective

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Nomenclature

Bu	dimensionless buoyancy parameter	*Re*	Reynolds number
d	diameter, m	*T*	temperature, °C
G	mass flux, kg/(m^2 s)	*U*	imposed voltage on test section, V
Gr	Grashof number		
h	heat transfer coefficient, W/(m^2 K)	*Subscripts*	
I	imposed current on test section, A	b	bulk properties
k	thermal conductivity, W/(m K)	cri	critical point
L	test section length, m	*i*	inner diameter
Nu	Nusselt number	pc	pseudocritical
P	pressure, MPa	v	quantities per unit volume
q	heat flux, kW/m^2	wi	inner wall
r	radius, m	wo	outer wall

condensation and pool boiling heat transfer characteristics of low-GWP alternatives including R1234ze(E), R1234ze(Z), and R1233zd (E). They concluded that the free convective condensation heat transfer coefficient of R1233zd(E) deviated from the theoretical value, most likely due to inaccuracies in the transport property data, and that the heat transfer coefficients of R1234ze(Z) and R1233zd(E) were slightly higher, but lower than those of R245fa. Huang et al. [9] conducted an experiment on the flow boiling pressure drop and heat transfer of R1233zd(E) in a multi-microchannel and developed a new empirical model suitable to high mass flux operating conditions. Lee et al. [10] conducted an experiment to investigate the heat transfer coefficient and pressure drop of R1233zd(E) in a brazed plate heat exchanger, and also carried out a comparison of its heat coefficient to the heat transfer coefficient of R245fa. The results showed that heat transfer coefficient of R1233zd(E) was approximately 9% lower than that of R245fa.

In this study, the heat transfer characteristics of R1233zd(E) (P_{cri} = 3.57 MPa, T_{cri} = 165.6° C) were investigated experimentally under supercritical pressures. A number of experimental investigation with various working fluid under supercritical pressure has been reported [11–29]. In a practical application involving the supercritical heat transfer, the flow passages are usually vertically located. Therefore, most experiments are conducted with a vertically circular tube. Some common features can be summarized from the experimental investigations. When the bulk fluid temperature is much lower than the pseudocritical temperature, the heat transfer coefficient shows similar characteristics to those of the fluid under subcritical pressures. As the bulk fluid temperature approaches the pseudocritical temperature, it increases monotonically and takes a maximum when the bulk temperature is slightly less than the pseudocritical temperature under the conditions with low heat fluxes. The vapor like fluid appears to dominate the heat transfer, which leads to a lower heat transfer coefficient when the bulk fluid temperature is high enough. As the heat flux increases, the maximum heat transfer coefficient observed near the pseudocritical point is suppressed. At a moderate heat flux, heat transfer deterioration takes place, which is manifested as a sudden increase in wall temperature. Such a heat transfer only occurs when the bulk fluid temperature is less than the pseudocritical temperature, whereas the wall temperature exceeds it. In addition, as obtained in various experimental investigations [12,13], the experimental pressures have little influence on heat transfer deterioration. The heat transfer will recover as the bulk fluid temperature increases to a value that is slightly lower than the pseudocritical temperature, characterized by a decrease in wall temperature.

With the knowledge of heat transfer characteristics of various working fluids from literatures and the results of R245fa (P_{cri} = 3.65 MPa, T_{cri} = 154.1 °C) in previous study [11], the working conditions were designed as follows: the heat flux ranged from 20 to 80 kW/m^2, whereas the mass flux were 400 and 600 kg/m^2 s. Then, the experiments were conducted under the pressure of 3.93 and 4.40 MPa, which were equal to the reduced pressure (P/P_{cri}) of 1.10 and 1.23, respectively. The inner diameter and length of the test tube were 4 mm and 1.04 m, respectively. The effects of mass flux, heat flux, and pressure are discussed based on the experimental data. Moreover, a comparison with the heat transfer coefficients of R245fa [14] was carried out and the results are presented in this paper.

2. Experimental facility and working conditions

The schematic of the experimental facility is shown in Fig. 1.

The experiment was conducted with the same experimental setup as that used for R245fa. Because the details of the test facility and the measurement procedure have been described in previous work [14], only a brief introduction is presented in this paper. The system consisted of the following components: a test section made of the sus-316, recuperator, water bath, magnetic gear pump, Coriolis type flowmeter, and preheater. During the experiment, the mass flow rate of the working fluid was controlled by the rotational speed of the pump and the bypass ratio. Additionally, the inlet temperature and pressure were controlled by the power supply of the preheater and the charged amount of the working fluid.

The measurement parameters included the inlet and outlet temperature of the test section, inlet pressure and local wall temperature of the test section, mass flow rate of the working fluid, and power supply to the test section. Two platinum-resistance temperature sensors were used to measure the inlet and outlet temperature of the test section. To measure the wall surface temperature, 53 K-type thermocouples were placed on the wall surface with an interval of 20 mm. A Coriolis type flow meter was used in order to measure the mass flow rate, while the imposed voltage and current were directly measured by the data logger. The local heat transfer coefficient was calculated based on these measurements.

The details of the thermocouple installation are illustrated in Fig. 2(a), and the method by which the thermal insulation of the test section was conducted is shown in Fig. 2(b). A glass fiber insulation layer was wrapped on the test tube, and rubber heater copper plates were installed on the surface of the layer. Another thin glass fiber layer and spiral duct holder were installed next to the rubber heater. During the experiment, the temperature of the copper plate was controlled by the rubber heater at a temperature close to the wall temperature of the test section. Consequently, the heat loss and temperature difference between the test tube and the surroundings were effectively reduced.