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Experimental study of in-tube cooling heat transfer and pressure drop characteristics of R134a at supercritical pressures

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ABSTRACT

The in-tube cooling flow and heat transfer characteristics of R134a at supercritical pressures are measured experimentally for various pressures and mass fluxes in a horizontal tube. The tube is made of stainless steel with an inner diameter of 4.01 mm. Experiments are conducted for mass fluxes from 70 kg/m^2 s to 405 kg/m^2 s and pressures from 4.5 MPa to 5.5 MPa. The inlet refrigerant temperature is from 80 °C to 140 °C. The results show that the refrigerant temperature, the mass flux and the pressure all significantly affect the flow and heat transfer characteristics of R134a at supercritical pressures. The experimentally measured frictional pressure drop and heat transfer coefficient are compared with predicted results from several existing correlations. The comparisons show that the predicted frictional pressure drop using Petrov and Popov's correlation accounting for the density and viscosity variations agree well with the measured data. Gnielinski's correlation for the heat transfer coefficient agrees best with the measured data with deviations not exceeding 25%, while correlations based on supercritical CO_2 heat transfer data overcorrect for the influence of the thermophysical property variations resulting in larger deviations. A new empirical correlation is developed based on the measured results by modifying Gnielinski's equation with thermophysical property terms including both the property variations from the inlet to the outlet of the entire test section and from the bulk to the wall. Most of the experimental data is predicted by the new correlation within a range of 15%.

1. Introduction

In the gas cooler of a trans-critical heat pump cycle, heat is rejected as sensible heat with no phase change occurs, so both the working fluid and the cooling fluid temperatures vary continuously. Thus, it is suitable for counter-current heat exchange process and for high-temperature heat generation. A wide temperature range is possible with moderate compressor pressure ratios with trans-critical cycles when the pressure and temperature are independent of each other and not restricted as in sub-critical cycles where the saturation pressure and temperature are not independent [1]. In addition, the trans-critical heat pump cycles work at higher pressures, which reduce the friction losses to give better performance. The size and complexity of the equipment are also reduced compared with the conventional sub-critical cycle.

Several conventional refrigerants including SF_6, C_3F_8, C_2HF_5, c-C_4F_8 have been proposed as working fluids for the trans-critical heat pump cycle with various performance characteristics [1]. The trans-critical heat pump cycle with R116 (C_2F_6) and R23 (CHF_3) as the working fluid have been analyzed theoretically [2,3]. R134a ($C_2H_2F_4$) is non-flammable, its ODP (ozone depleting potential) is zero and its GWP (global warming potential) is much lower than for R23 and R116, thus, R134a has been widely used as a refrigerant for domestic refrigerators and automobile air conditioners. R134a is more suitable as the working fluid in trans-critical cycles for high-temperature heat generation because of its higher critical temperature (compared with R23 and R116) and lower operating pressure (compared with trans-critical heat pumps with CO_2 as the working fluid), as well as its fairly good thermophysical properties and good thermal stability. Supercritical cycles with R134a as the working fluid for geothermal power generation system has been proposed and studied [4].

When the R134a is above the critical pressure (p_{cr} = 4.06 MPa for R134a), as shown in Fig. 1, the specific heat variation with temperature shows a sharp peak at a specific temperature which is defined as the pseudo critical temperature, T_{pc}. This temperature increases with increasing pressure. Other properties including the density, thermal conductivity and viscosity vary also significantly within a small range of temperature in the vicinity of T_{pc}. With these thermophysical characteristics, the flow and heat transfer of supercritical R134a will be strongly influenced and quite different from those of fluids with constant thermophysical properties, such as working fluids in conventional cycles at sub-critical pressures.

There have been many papers published on internal forced and mixed flow and heat transfer of supercritical fluids in-tubes. Most

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Nomenclature

A	heat transfer area, m^2
c_p	specific heat, J/kg K
d	diameter, m
f	friction factor
G	mass flux, kg/m^2 s
H	enthalpy, J/kg
h	heat transfer coefficient, W/m^2 K
L	length, m
$LMTD$	logarithmic mean temperature difference
Nu	Nusselt number
ΔP	pressure drop, kPa
P	pressure, MPa
Pr	Prandtl number
q	heat flux, W/m^2
Re	Reynolds number
T	temperature, °C
u	velocity, m/s

Greek symbols

μ	viscosity, Pa s
ρ	density, kg/m^3
λ	thermal conductivity, W/m K

Subscripts

ad	adiabatic section
b	bulk
cf	cooling fluid
con	contraction
cooling	cooling section
f	frictional
in	inlet
out	outlet
pc	pseudo critical
re	refrigerant (R134a)
w	wall temperature
vp	properties variation

of these studies have focused on the local heat transfer characteristics of water and CO_2 at supercritical pressures in heat absorbing processes for use as coolants in Supercritical Pressure Water-cooled Reactor (SPWR), high temperature CO_2 cooled reactor and other related applications in power engineering, aerospace engineering, and chemical engineering [5–8]. In these applications, in addition to the calculation of the integral heat transfer performance, to predict the local heat transfer data is very important to avoid the local burnout of the wall due to local high temperature resulted from local heat transfer deterioration; thus, several correlations for calculating the local heat transfer were established [5–7] in a form of $Nu = Nu_x$. Only the radial property variations need to be corrected to predict the local heat transfer. A number of detailed reviews covering the studies on heat transfer to fluids at supercritical pressures during heating can be found in the literature, for example, Petukhov [9], Hall [10], Jackson et al. [11], Kurganov and Kaptilnyi [12], and Kurganov [13].

In recent years, the convection heat transfer of fluids at supercritical pressures during heat rejection has also been investigated for small and micro size tubes and channels driven by the need for light and small heat exchangers in trans-critical air-conditioning and heat pump systems. In this situation, mean (or axially-averaged) heat transfer data and correlation that enables the calculation of the mean heat transfer coefficient regarding only the inlet and outlet or average bulk temperature (the average of inlet and outlet refrigerant temperature) is of great interest for designers to enhance the integral heat transfer performance in the trans-critical heat pump cycle.

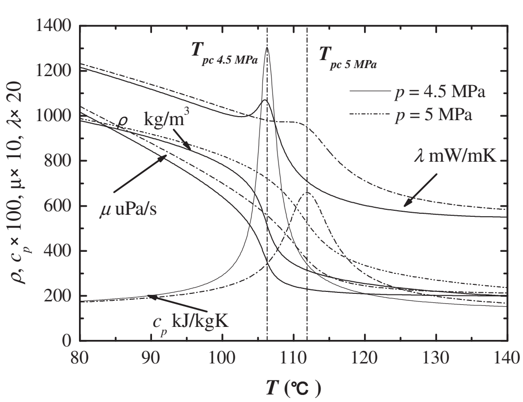

Fig. 1. Physical properties of R134a at supercritical pressures.

In most trans-critical heat pump or air-conditioning systems, natural CO_2 refrigerant are used as working fluid; thus, previous studies mainly focused on the flow and heat transfer characteristics of CO_2 during cooling. Pettersen et al. [14] investigated the mean heat transfer coefficient of supercritical CO_2 in multi-port mini-channels for cooling conditions in channels with an inner diameter of 0.79 mm. They found that Gnielinski's correlation for the single-phase heat transfer coefficient agreed reasonably well with the experimental results. Liao and Zhao [15] experimentally investigated mean convection heat transfer coefficient for carbon dioxide at supercritical pressures in horizontal mini/micro circular tubes having 0.50, 0.70, 1.1, 1.40, 1.55, and 2.16 mm diameters. Dang and Hihara [16] experimentally investigated the effects of mass flux, pressure, and heat flux on the axially-averaged heat transfer coefficient and pressure drop of CO_2 at supercritical pressures during cooling for horizontal tubes with inner diameters ranging from 1 to 6 mm and proposed a modified Gnielinski equation to predict the heat transfer coefficient of supercritical carbon dioxide during the heat rejection process. Yoon et al. [17] presented experimental data for the convection heat transfer characteristics during the gas cooling process of carbon dioxide in a horizontal 7.73 mm inner diameter copper tube for various mass fluxes and pressures, and proposed an empirical correlation based on their experimental data to predict the near-critical heat transfer coefficient. Jiang et al. [18] measured the local heat transfer coefficient in a 2 mm vertical tube for cooling conditions and discussed the effects of pressure, mass flux and buoyancy on the local heat transfer. Recently, several studies have been published on the in-tube flow and heat transfer of supercritical pressure CO_2 with entrained lubricating oil [19–22] with a empirical correlation developed to evaluated the heat transfer coefficient of the supercritical pressure CO_2/lubricating oil mixture in the gas cooler in actual applications [22]. Other studies include Huai et al. [23], Son and Park [24], etc. The existing correlations for the heat transfer of supercritical fluids for cooling conditions are summarized in Table 1.

The flow and heat transfer characteristics of HFC refrigerants have also been widely investigated experimentally, but most of these studies have focused on evaporation and condensation pro-