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Two layer heat transfer model for supercritical fluid flow in a vertical tube

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ABSTRACT

Experimental heat transfer data in a supercritical vertical upward CO_2 flow were analyzed, based on the relationship between the wall heat flux and mass flux, buoyancy and flow acceleration effects, and specific heat variation across the turbulent boundary layer. These analyses indicated that the flow acceleration and significant specific heat variation in the boundary layer greatly influenced the heat transfer phenomena under the tested experimental conditions. A two layer heat-transfer model that sufficiently reflects both the effects of flow acceleration and specific heat variation was proposed to quantify the heat-transfer characteristics of supercritical fluids. This model was based on the thermal resistance behavior in the viscous sub-layer and the buffer layer. In our assessment of this model, the Nusselt number calculated from various experiments agreed with our data within a margin of error of ±30%. Also, the location of the peak inner wall temperature from experimental data almost coincided with the peak maximum thermal resistance in the viscous sub-layer, calculated using the proposed model.

1. Introduction

Turbulent forced convective heat-transfer phenomena of supercritical fluid flow in a vertical circular tube have much more complex characteristics than general single-phase flows at subcritical pressures, due to significant variations of thermo-physical properties. In particular, large differences in density between bulk and wall positions and along the flow direction can change the flow structure and affect the turbulence in the flow. In previous research, these density variation effects have been represented as the buoyancy and flow acceleration. Extreme variations in density between the bulk and wall fluids can change the flow structure and affect the turbulence of the flow, via the action of buoyant force. When the heat flux to the fluid is high, the difference between the wall and bulk-fluid densities becomes large enough to induce significant buoyant force in the fluid flow, and the buoyancy effect changes the flow structure. Turbulence in the flow is maintained by an energy input generated by the shearing of the fluid by the mean velocity gradient. Turbulent diffusivity is reduced when the low-density wall layer becomes thick enough to reduce the shear stress in the region where energy is normally fed into the turbulence [1].

During strong heat transfer to a supercritical fluid in a tube, the fluid flow is greatly accelerated by thermal expansion effects. When this flow acceleration effect is extreme, the turbulent boundary layer in the fluid can be relaminarized, and the heat transfer rate into the fluid is significantly reduced [2–7]. McEligot et al. [8] studied heat transfer during the transition from turbulent to laminar flow. They claimed that this phenomenon was caused by flow acceleration, due to strong heating. Hall [1] presented a physical mechanism for the local deterioration in the heat-transfer coefficient of supercritical fluid flow. Hall reported that when the low-density layer became thick enough to reduce the shear stress in the region where energy is normally fed into the turbulence, the diffusivity for heat was reduced. Tanaka et al. [9] studied the shear-stress distribution in a vertical tube by taking into consideration the buoyancy force as well as the inertia force due to acceleration. By examining how the velocity profile depended on the shear-stress gradient at the wall, they deduced criteria for the prominent effects of buoyancy and acceleration. Jackson and Hall [10] investigated the influences of buoyancy on heat transfer in fluids flowing in vertical tubes under turbulent conditions. They described the mechanism of heat transfer impairment due to buoyancy based on theoretical considerations. Kurganov and Kaptilnyi [11] studied experimentally the velocity and temperature fields in a supercritical CO_2 flow through a heated vertical circular tube. They reported that the heat-transfer coefficient deterioration was due to the formation of a fluid layer in the turbulent core with lower values of eddy diffusivity. Jiang et al. [12] investigated convection heat transfer of supercritical CO_2 in a 0.27-mm-diameter vertical mini-tube, experimentally and numerically. Their results indicated that the flow direction, buoyancy, and flow acceleration had little influence on the local wall temperature. He et al. [13] performed computational simulations of turbulent convection heat transfer experiments of supercritical CO_2; the buoyancy effect was generally insignificant in their results. They reported that the heat transfer could

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Nomenclature

A_{in}	area of the test tube inner surface (m^2)
Bo^*	buoyancy parameter, $Gr*/(Re_b^{3.5}Pr_b^{3.5})$
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
$\bar{c}_p$	mean specific heat (kJ kg^{-1} K^{-1}), $(i_w - i_b)/(T_w - T_b)$
C	constant
D	tube diameter (m)
f	friction factor
g	gravitational acceleration (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
Gr^*	Grashof number, based on heat flux, $g\beta_b D_{in}^4 q''_w/(\nu_b^2 k_b)$
h	heat-transfer coefficient (W m^{-2} K^{-1})
i	enthalpy (kJ kg^{-1})
k	thermal conductivity of fluid (W m^{-1} K^{-1})
k_s	thermal conductivity of solid material (W m^{-1} K^{-1})
L	tube length (m)
Nu	Nusselt number, hD/k
P	pressure (bar)
Pr	Prandtl number, $c_p\mu/k$
q^+	non-dimensional heat flux, $q''_w\beta_b/(Gc_{p,b})$
q_V	volumetric heat generation rate (W m^{-3})
q''_{loss}	local heat-loss flux (W m^{-2})
q''_w	local wall heat flux (W m^{-2})
Q	total heat-transfer rate (W)
r	radial coordinate (m)
R	thermal resistance (K W^{-1})
Re	Reynolds number, GD/μ
T	temperature (°C or K)
u	mean velocity of flow (m s^{-1})
x	axial distance (m)
Greek symbols	
β	volume expansion coefficient (K^{-1})
δ	boundary layer thickness (m)
δ^+	non-dimensional boundary-layer thickness
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
τ_w	shear stress at the wall (N m^{-2})
$\Delta\tau_{ac}$	reduction of shear stress due to flow acceleration (N m^{-2})
σ	uncertainty of measured parameter
Subscripts	
ac	flow acceleration
b	evaluated at bulk
BFL	buffer layer
cr	critical
FTR	fully turbulent region
i, in	inner, inlet
iso	isothermal fluids
o	outer
pc	pseudo-critical
VSL	viscous sub-layer
w	evaluated at the wall

be significantly impaired as a result of flow acceleration when the heating was strong, which caused a reduction in turbulence production.

Some other researchers have focused on the behavior of the turbulent boundary layer (viscous sub-layer and buffer layer) near the wall. The thickness variation of the viscous sub-layer, due to the shear stress being changed by flow acceleration and buoyancy, can significantly affect the heat diffusion from the wall to the flow core, because the viscous sub-layer has a large thermal resistance in a turbulent boundary layer. Also, significant variation in the thermo-physical properties of supercritical fluids in the boundary layer can affect the heat-transfer phenomena considerably. Petukhov et al. [14] investigated experimentally the worsening heat transfer conditions for CO_2 turbulent flow at supercritical pressure. In their experiments, local worsening of heat transfer was clearly observed at low and moderate mass-flow rates, but no worsening of the local heat transfer occurred at a high mass flow rate. To obtain criteria to describe the start of the deterioration of heat transfer, they used an approach based on a three layer model of turbulent flow, and considered the displacement of a zone with a sharp change in the buffer layer region. Bazargan and Mohseni [15] focused on the significance of the buffer zone in the boundary layer. Their results showed that in an enhanced heat transfer regime, a heat transfer coefficient peak occurred when the pseudo-critical temperature, or maximum heat capacity, was located within the buffer layer. They also reported that in the deteriorated heat transfer regime, the extent of the laminar sub-layer appeared to be changed so that the buffer zone was further away from the wall.

The heat-transfer phenomena in supercritical fluid flows are closely related to the behavior of the turbulent boundary layer near the wall (*i.e.*, the viscous sub-layer and buffer layer). However, except for a few numerical studies [16,17], most research has focused on the overall heat transfer and has not directly considered the deformation of the turbulent boundary layer near the wall, due to the drastic thermo-physical property variations in supercritical fluids.

The aim of the present study was to present a heat transfer model for supercritical fluid flow that considers the behavior of the turbulent boundary layer near the wall. To achieve this, turbulent heat-transfer experiments with vertical upward supercritical CO_2 flow were conducted in a circular tube with an inner diameter of 4.5 mm. A heat-transfer model based on the thermal resistance in the viscous sub-layer and buffer layer regions was established and assessed using experimental data.

2. Experimental

2.1. Experimental loop and test section

An experimental loop (Fig. 1) was designed and constructed to quantify the heat transfer in supercritical CO_2 vertical upward flow. An air-driven liquid pump was operated with pressurized air to pressurize the CO_2; the air was supplied and controlled using a constant-pressure electric regulator. The CO_2 (purity 99.5%) was pressurized from the liquid state (~50 bar) in a container equipped with a siphon. A magnetic gear pump was installed in the loop to circulate the working fluid. The flow rate of the working fluid was controlled by the motor rotation speed (rpm) controller and adjusted using a needle valve attached in the flow bypass line of the loop. The mass flow rate was measured using a Coriolis mass-flow meter, which had a measurement range of 0.05–2.5 kg/min, an accuracy of 0.1% (full scale), and a repeatability of 0.05%. The working fluid supplied from the pump was heated to the desired inlet temperature by passing it through a circulation pre-heater, which was controlled using a PID temperature controller. The test section was heated electrically using a DC power supply to supply a uniform heat-generation rate.

A test tube was constructed of stainless steel 316L seamless tube with inner and outer diameters of 4.5 mm and 6.3 mm, respectively. The heated length of the test section was 900 mm (L/D_i = 200). In consideration of the combined thermal and hydraulic entry region,