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Numerical investigation of buoyancy effect on heat transfer to carbon dioxide flow in a tube at supercritical pressures

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ABSTRACT

A numerical analysis of the buoyancy effect on heat transfer to carbon dioxide flow at supercritical pressures in a vertical heated tube has been carried out using the FLUENT computational fluid dynamics (CFD) tool with the shear-stress-transport low Reynolds number eddy viscosity turbulence model. It covered the 1200-mm heated section and included 500-mm unheated section upstream for flow development. Wall temperatures calculated from the analysis were compared against those obtained from the experiments. Although the analysis overestimated the experimental wall temperatures, it captured appropriately the general trends of the experimental results. Based on the examinations of the calculated flow and turbulence fields, the effect of buoyancy on heat transfer has been quantified. Results showed that there are two obvious characteristics of the velocity gradient profile influenced by severe buoyancy effect, i.e., (1) zero-velocity-gradient region may come into being; (2) the slope of the velocity gradient profile near the wall may become very large. When the zero-velocity-gradient region comes into the rim of viscous sub-layer, turbulent production and diffusion will be damped, finally deteriorated heat transfer occurs. Enhancement heat transfer may happen at the post-deteriorated heat transfer section because of the large slope of the mean velocity gradient profile, and the possible mechanism was introduced. A striking phenomenon has been found, i.e., enhancement heat transfer might also happen when the buoyancy parameter is lower the value corresponding to heat transfer recovery. This phenomenon relates to the difficulty of heat transfer data correlation near the pseudo-critical point.

1. Introduction

New applications with fluids at supercritical pressures have been considered for power generation with enhanced efficiency and safety. In addition to the supercritical boilers and supercritical water-cooled reactors, the supercritical carbon dioxide (CO_2) Brayton cycle has been adopted for power generation systems, such as gas/liquid–metal cooled reactors [1], fast reactors [2], fusion reactors [3], biomass and bio-energy power conversion systems [4], and renewable energy systems [5]. Furthermore, the use of CO_2 at supercritical pressures has also been explored in the development of innovative mini or compact gas coolers and internal heat exchangers for the CO_2 high pressure trans-critical compression cycles in air-conditioners and heat pumps [6,7]. An accurate prediction of the convective heat transfer is crucial for establishing efficiency and safety of these new applications.

Supercritical fluids under heating do not exhibit a phase change as the temperature increases. However, thermal properties vary dramatically near the pseudo-critical point, as shown in Fig. 1, affecting significantly the heat transfer characteristic. The radial and axial variations of fluid temperature under heated or cooled conditions further complicate the phenomena impacting the effectiveness of heat transfer. A considerable number of experimental, theoretical and numerical studies on heat transfer to fluids at supercritical pressures have been performed over the last decades [8–21]. Efforts have been focused on the buoyancy effect on heat transfer due to the non-uniform density distribution over the cross section of the channel and on the flow acceleration or deceleration effect on heat transfer due to expansion or contraction, respectively, of the fluids as a result of significant axial variations of bulk fluid density under heating or cooling conditions.

Dimensionless numbers, as well as their thresholds, have been introduced to determine the onset, or the domination, of buoyancy and flow acceleration effects on heat transfer [12,17,22–24]. These numbers were based on experimental data obtained with simple channels such as tubes and annuli. Most analyses applied one of

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Nomenclature

$\mathbf{Bo}^*$	buoyancy parameter defined by Jackson et al., as shown in Eq. (6)
Bu	buoyancy parameter defined by Liu et al., as shown in Eq. (8)
Cp	specific heat at constant pressure, J/kg/°C
D	diameter, m
E	specific inner energy, J/kg
g	gravity acceleration, 9.8 m/s^2
$\mathbf{Gr_b}$	Grashof number based on the bulk fluid condition, defined in Eq. (9)
$\mathbf{Gr_q}$	Grashof number based on the wall heat flux, defined in Eq. (7)
H	specific enthalpy, J/kg
HTC	heat transfer coefficient, W/m^2/°C
m	mass flux, kg/m^2/s
p	pressure, Pa
Pr	Prandtl number, $= \mu C_P/\lambda$
q	heat flux, W/m^2
r	radial distance, m
R	radius, m
Re	Reynolds number, $= \rho UD/\mu$
T	temperature, °C
u	axial velocity, m/s
U	velocity, m/s
x	axial distance, m
y	radial distance, m

Greek symbol

β	volumetric expansion coefficient, 1/K
$\bar{\rho}$	averaged density of fluid, kg/m^3
ρ	density, kg/m^3
λ	thermal conductivity of fluid, W/m/°C
μ	viscosity, Pa s
ν	momentum viscosity, m^2/s

Subscripts

b	bulk-fluid condition
e	referring to effective
exp	from experiments
i	referring to the order of dimension
pc	pseudo-critical condition
t	related to turbulence
w	near wall value

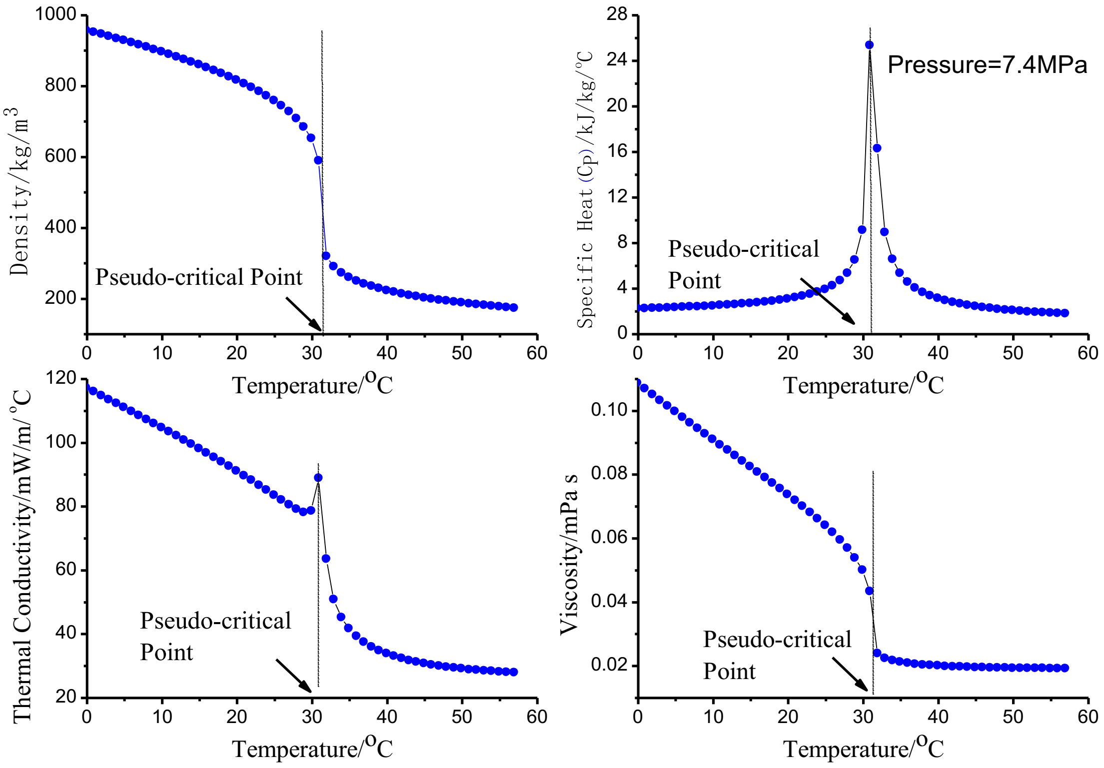

Fig. 1. Thermal properties variations with temperature for carbon dioxide at 7.4 MPa [8].

these dimensionless numbers to quantify the implication of the buoyancy or the flow acceleration effect in specific heat-transfer regions [25,26]. When the heat flux is increased enough, the situation of deteriorated heat transfer often occurs (regime A as shown in Fig. 2). The localized wall temperature rise has been concluded as the result that the profiles of velocity distribution and shear stress distribution are distorted substantially which is closely associated with buoyancy effect. And there is a trough of the wall temperature just at the downstream of the peak wall temperature. It's analyzed that the trough of the wall temperature is related to the relatively large specific heat of the bulk fluid at least. As a strong convective process, the distorted distribution of velocity and shear stress at regime A might make a big difference on the heat transfer from the heated wall to the bulk fluid at regime B. While almost no