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Improvement of buoyancy and acceleration parameters for forced and mixed convective heat transfer to supercritical fluids flowing in vertical tubes

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ABSTRACT

An analytical approach is applied to examine the buoyancy and acceleration effects on forced and mixed convective heat transfer at supercritical pressures. Two non-dimensional parameters have been developed for these effects. In the process of developing the buoyancy parameter (Bu), a new relationship between momentum and thermal boundary layer was used. And the van der Waals equation was adopted in developing acceleration parameter (Ac). Thresholds of Bu and Ac have been theoretically established as 1.3×10^{-5} and 3.3×10^{-6}, respectively. These non-dimensional parameters were validated against experimental data obtained with carbon dioxide flowing through a heated tube upward and downward vertically. With the help of the developed Bu, Ac and their thresholds, the complicated experimental phenomena can be explained more reasonably. A heat-transfer correlation has been developed, in terms of these buoyancy and acceleration numbers, with an extensive supercritical carbon dioxide heat-transfer database. It provides better prediction accuracy than three other correlations with 90% of the experimental data predicted within the ±30% error range.

1. Introduction

Supercritical carbon dioxide (SCO_2) Brayton Cycle has been proposed as the power conversion system for advanced nuclear energy systems [2015 GIF Annual Report]. Carbon dioxide is selected as the working fluid due to its low critical temperature and pressure (31.0 °C, 7.38 MPa), compressible, abundant in reserves and having a relatively good neutron physical property and thermal stability in a moderate design temperature range of nuclear reactor [1]. Operating at supercritical pressures would improve the thermal efficiency, avoid the boiling crisis in heat transfer due to absence of phase change, and reduce the turbine size [2].

Convective heat transfer between coolant and components is the primary heat exchange mode in the reactor core, recuperator, pre-cooler and safety systems and equipments [3]. It is a complicated phenomenon at supercritical pressures as the coolant temperature increases from subcritical to supercritical conditions passing through the pseudo-critical point where rapid changes in thermal physical properties are encountered. Fig. 1 illustrates the variations of density, thermal conductivity, specific heat and dynamic viscosity with temperature at the pressure of 7.4 MPa for carbon dioxide. Density and dynamic viscosity decrease monotonically with temperature rising up albeit much steeper reduction at the vicinity of the pseudo-critical point. Variations of specific heat and thermal conductivity with temperature are a bit more complex. The specific heat increases gradually with temperature at subcritical conditions but becomes sharply as the temperature approaches the pseudo-critical point, beyond which the specific heat decreases sharply first and then gradually recovers as the temperature increases at supercritical conditions. These non-linear variations in fluid properties have led to complex heat-transfer characteristics, which have been the subject of many previous studies.

Variations in fluid properties are further complicated inside a heated tube, where the fluid temperature changes in both the axial and radial directions. As an illustration, Fig. 2 shows variations of density, dynamic viscosity and specific heat in axial and radial directions inside a uniformly heated tube of 6-mm inside diameter (ID) with assumptions of supercritical temperature at the wall and subcritical temperature at the free stream. In addition, the pseudo-critical point is assumed locating at the mid-zone between the centre and wall of the heated tube. Both the density and dynamic viscosity decrease along the flow direction and from the centre to the

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Nomenclature

Ac	flow acceleration parameter, defined in the context
Ac*	the threshold of Ac
Bo	buoyancy parameter, $=Gr_b/Re_b^{2.7}$
Bu	buoyancy parameter, defined in the context
Bu*	the threshold of Bu
c_p	specific heat of fluid at constant pressure (J/(kg·°C))
$\overline{c_P}$	averaged specific heat of fluid at constant pressure, $=(h_w - h_b)/(T_w - T_b)$
D	diameter (m)
g	gravitational acceleration (m/s²)
Gr_b	Grashof number, $=(\rho_b - \bar{\rho})gD^3/(\rho_b \nu_b^2)$
h	enthalpy (J/kg)
HTC	convective heat transfer coefficient (W/(m²·°C))
k	thermal conductivity of fluid (W/(m·°C))
Kv	flow acceleration parameter, $=4q^+/Re_b$
m	mass flux (kg/(m²·s))
Nu	Nusselt number, = hD/k
P	system pressure (Pa)
Pr	Prantal number, $=\mu c_P/k$
$\overline{Pr}$	averaged Prantal number, $=\mu\overline{c_P}/k$
q	wall heat flux (W/m²)
q^+	non-dimensional heat flux, $=q_w/(c_{P,b}T_b m)$
R	pipe radius (m), or universal gas constant (8.314 kJ/(kmol·°C))
Re	Reynolds number, $=uD/\nu$
T	temperature (°C)
u	velocity (m/s)
V	specific volume (m³/kg)
x	distance to the y axis (m)
y	distance to the x axis (m)

Greek symbol

α_P	volumetric expansion coefficient (1/T)
β_T	volumetric compression coefficient (1/Pa)
δ	effect thickness of buoyancy or acceleration effect (m)
μ	viscosity (Pa·s)
ν	kinematic viscosity (m²/s)
ρ	density (kg/m³)
$\bar{\rho}$	mean density over the thermal boundary layer, $=\int_{T_b}^{T_w} \rho dT/(T_w - T_b)$
τ	shear stress (Pa)

Subscripts

ac	referred to acceleration effect
b	referred to bulk condition
bu	referred to buoyancy effect
cal	referred to calculated value
exp	referred to experimental value
M	referred to the momentum layer
pc	referred to pseudo-critical condition
ref	referred to reference
T	referred to the thermal layer
w	referred to near the wall

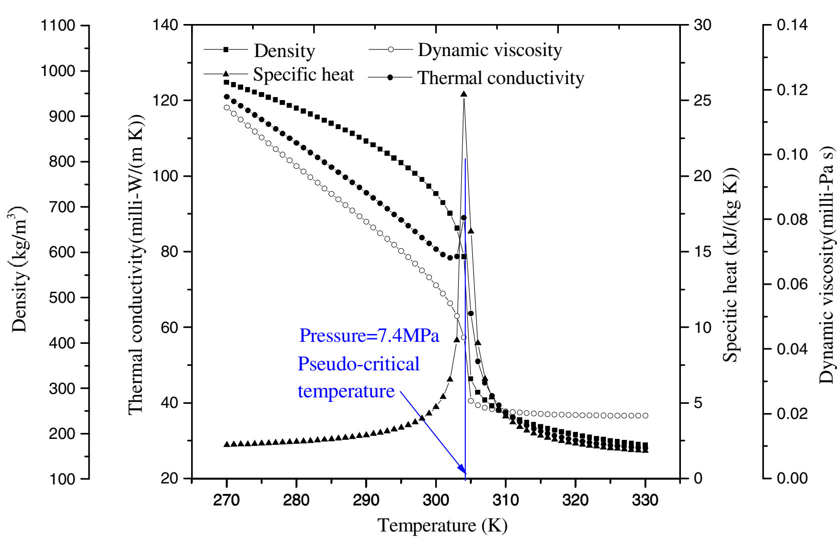

Fig. 1. Physical-property variations near the pseudo-critical point of carbon dioxide.

wall of the tube. As indicated previously, sharp reductions of density and dynamic viscosity are shown at the vicinity of the pseudo-critical point over the radial direction. The variation of specific heat is more complex. It increases slightly at the centre of the tube but decreases at the wall of the tube along the flow direction, which are attributed to the temperature increase at these locations. The specific heat increases sharply as the fluid temperature approaches the wall. These complex variations would exert additional buoyancy and inertia force on the flow that change the flow structure and the strength of turbulence resulting in enhanced or deteriorated convective heat transfer [4–11]. Fluid-property variations induce buoyancy and flow acceleration effects on the convective heat transfer [4–6,10,12,13,18]. A strong buoyancy effect changes the ‘U’ shape velocity profile to ‘M’ shape on the cross-section [14]. This change reduces the shear stress in the rim of viscous sub-layer, where energy is normally fed into turbulence, and affects turbulent eddy production and diffusivity. In the case of fluid heated with a high heat flux, the fluid can be accelerated through volume expansion duo to temperature rising and pressure dropping. A strong flow acceleration effect could transform the turbulent boundary layer to a laminar boundary layer as a result reducing the heat transfer rate to the fluid [13,15]. McEligot et al.