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Investigation of buoyancy-enhanced heat transfer of supercritical CO_2 in upward and downward tube flows

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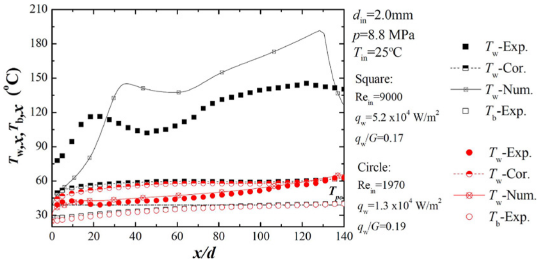
GRAPHICAL ABSTRACT



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ABSTRACT

The heat transfer enhancement (HTE) from buoyancy occurs in upward and downward flows at supercritical pressures when the buoyancy parameter, Bo*, is above 8×10^{-6}. Numerical simulations of experiments on buoyancy-enhanced heat transfer of supercritical CO_2 in a heated vertical tube with an inner diameter of 2.0 mm at an inlet Reynolds number, Re_{in}, of 1970 were performed using low Reynolds number turbulence models. The Myong and Kasagi (MK) model quantitatively predicted the buoyancy-enhanced heat transfer. The trade-off between buoyancy effect on the viscous length scale and the redistribution of velocity profiles resulted in similar heat transfer results although the mechanisms on the two aspects were different for upward and downward flows. Heat transfer deterioration (HTD) occurred in upward flow as Re_{in} increased. The supercritical heat transfer in upward flows for various Re_{in} were compared to obtain a better understanding of the buoyancy effect under HTE and HTD conditions.

1. Introduction

Studies on the in-tube flow and convective heat transfer to fluids at supercritical pressures have been received increased attention with the rapid development of an advanced nuclear reactor, specifically, the supercritical pressure water-cooled reactor (SCWR). This reactor involves a simpler and more compact system, and potentially a higher thermal efficiency than that of current light-water reactors (LWR) [1,2]. The heat transfer coefficient predictions from the reactor core to the coolant in the cooling passages are difficult owing to the significant changes in the thermophysical properties at supercritical conditions, including the density, viscosity, specific heat, thermal conductivity, etc. [3].

The special characteristics and complicated mechanism of the heat transfer of fluids at supercritical pressures in vertical tubes are from the sharp variation in the thermophysical properties, buoyancy effect and

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Nomenclature

Bo*	Non-dimensional buoyancy parameter, $Gr^*/(Re^{3.425}Pr^{0.8})$
c_p	Specific heat, [J/kg K]
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	Constants in the ε-equation
D	Additional term in the k equation
d	Diameter, [mm]
E	Additional term in the ε equation
f_1, f_2	Function in the ε equation
f_μ	Damping function
g	Acceleration due to gravity, [m/s^2]
G	Mass flow rate, [kg/(m^2 s)]
G_k	Buoyancy production of turbulent kinetic energy, [kg/(m s^3)]
Gr*	Grashof number, $\beta g d^4 q_w/(\lambda u^2)$
h	Bulk specific enthalpy, [J/kg]
L	Energy containing scale or heated length, [m]
k	Turbulent kinetic energy, [m^2/s^2]
Nu	Nusselt number
Nu_f	Nusselt number for forced convection
Kv	Non-dimensional flow acceleration parameter
p	Pressure, [MPa]
P_k	Turbulent shear production, [kg/m·s^3]
Pr	Prandtl number, $\mu c_p/\lambda$
q_w	Heat flux, [kW/m^2]
r	Radial coordinate [m]
R	Tube radius [m]
Re	Reynolds number, UD/ν
T	Temperature, [°C]
u,v	Velocity components in the x, r directions, [m/s]
$-\overline{u'v'}$	Turbulent shear stress, [m^2/s^2]
x	Axial coordinate, [m], or distance from the position where heating starts in the axial direction
y	Distance from the wall in the normal direction, R-r, [m]
$y+$	Non-dimensional distance from the wall, $\frac{y}{\nu}\sqrt{\tau_w/\rho}$

Greek symbols

α_p	Thermal expansion coefficient, [1/K]
β_T	Isothermal compression coefficient, [1/MPa]
ε	Dissipation rate, [m^2/s^3]
λ	Thermal conductivity, [W/(m K)]
μ	Dynamic viscosity, [Pa s]
μ_t	Turbulent dynamic viscosity, [Pa s]
η	Dissipation scale (Kolmogorov scale), [m]
ν	Kinematic viscosity, [m^2/s]
ν_t	Turbulent kinematic viscosity, [m^2/s]
ρ	Density, [kg/m^3]
σ_T,	Turbulent Prandtl number
σ_k, σ_ε	Turbulent Prandtl numbers for the k and ε equations
τ	Shear stress, [Pa]

Subscripts/over-bars

b	Bulk
cor	Predictions using correlation
exp	Experimental measurements
in	Inlet or inner
p	Induced by pressure drop
pc	Pseudo-critical
T	Induced by temperature variation
w	Wall temperature
"-"	Over-bar used for conventional average
"~"	Over-bar used for the Favre average

thermal acceleration effect during heating. The flow and heat transfer characteristics of supercritical CO_2 in various channels was reviewed by Rao et al. [4]. In flow channels with a medium scale as in the cooling passages in the SCWR, the buoyancy effect from the radial density variation was dominant [5]. The heat transfer deteriorated or was enhanced depending on the dimensionless buoyancy parameter Bo*, as shown in Fig. 1. The buoyancy parameter is related to the Grashof number, Reynolds number and Prandtl number, defined as $Bo^* = Gr^*/(Re^{3.425}Pr^{.8})$ [6,7].

According to McEligot and Jackson [6,7], the heat transfer is deteriorated due to the buoyancy for upward flows with $6 \times 10^{-7} < Bo^* < 1.2 \times 10^{-6}$. The ratio of Nusselt number to the corresponding value in forced convection conditions, Nu/Nu_f, is less than 0.9, indicating that heat transfer rate is reduced by more than 10% from that of the forced convection. The heat transfer deterioration gradually decreases as the Bo* increases for $1.2 \times 10^{-6} < Bo^* < 8 \times 10^{-6}$, but the buoyancy still negatively affects the heat transfer. Generally, the buoyancy-induced heat transfer deterioration (HTD) is a significant issue related to the security of the reactor core of the SCWR. The criterion and quantitative predictions of the HTD are important for the thermal hydraulic design and optimization of the reactor core of the SCWR. In the buoyancy-deteriorated heat transfer cases reported by Shitsman [8], Li et al. [9], and Bae et al. [10], large localized heat transfer deterioration was observed in the upward flow cases with local wall temperatures significantly higher than those in the corresponding downward flow cases. In these cases, Bo* ranged within $6 \times 10^{-7} < Bo^* < 8 \times 10^{-6}$, and the heat transfer deteriorated from the buoyancy in the upward flow, while the heat transfer was enhanced in the downward flow, as shown in Fig. 1. The influence of the buoyancy resulted in a large discrepancy of the local wall temperature variations for the upward and downward flow cases with equal mass flow rate and heat flux. When Bo* further increased, which indicated a stronger buoyancy, the heat transfer was enhanced for the upward and downward flows. In addition, the difference in the heat transfer and local wall temperature variations in the upward and downward flow cases rapidly decreased. There are only a few studies on the heat transfer enhancement (HTE) in the upward tube flow. Investigations of the HTD and HTE are both important to understand the mechanism of the buoyancy effect on the heat transfer of supercritical pressure fluids. However, there are minimal experimental data reported and discussed for the strong buoyancy-affected heat transfer conditions at supercritical pressures with a high value of Bo*, of above 8×10^{-6}.

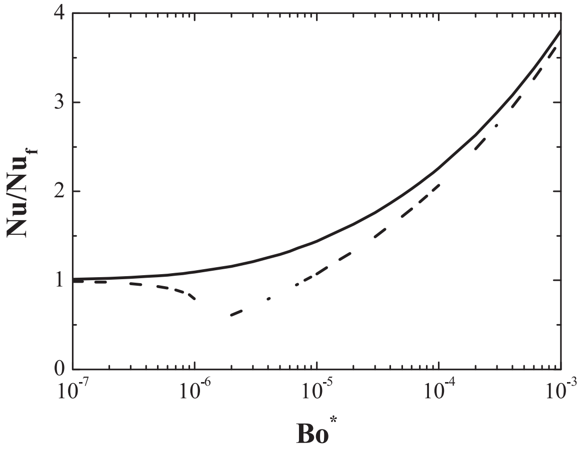

Fig. 1. Nusselt number ratio variation with buoyancy parameter for (—) downward and (—) upwardflows [6].