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Buoyancy effects on turbulent heat transfer of supercritical CO_2 in a vertical mini-tube based on continuous wall temperature measurements

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ABSTRACT

Convection heat transfer of supercritical pressure fluid is important in industrial applications such as supercritical power stations, the supercritical CO_2 Brayton cycle, Carbon Capture Utilization and Storage, and the thermal protection for rocket thrusters. Previous research has confirmed that there are three heat transfer regions for convection heat transfer of supercritical pressure fluid flowing inside vertical tubes: normal heat transfer, heat transfer deterioration, and heat transfer enhancement. However, existing research still carries inconsistent results, especially regarding the onsets of heat transfer deterioration of supercritical pressure fluid flow in vertical tubes. Here we propose a new view, by estimating the location where local fluid temperature, $T_f(r)$ equals to the pseudocritical temperature, T_{pc}, in the transversal section inside the tube, then analyzing the relationship between the location where $T_f(r) = T_{pc}$ and the turbulent boundary layers in the near wall region, to identify buoyancy effects on turbulent heat transfer. By taking advantage of infrared thermometry measurement to achieve continuous wall temperature, theoretical analysis was validated by experiments of supercritical pressure CO_2 in a vertical mini-tube with inner diameter of 0.953 mm. The experiments were performed for a pressure of 7.6–9.5 MPa, inlet mass flux from 255 kg/m^2 s to 685 kg/m^2 s, and heat flux from 12 kW/m^2 to 63 kW/m^2. It is found that in contrast with the previous results, when the value of y^+ at the location of $T_f(r) = T_{pc}$, $y^+|_{T_{f(r)}=T_{pc}}$, less than 5, heat transfer enhances for upward and decreases for downward flow due to the buoyancy effect. With the heat flux increasing or mass flux decreasing, the buoyancy effect on the turbulent convection heat transfer characteristics of supercritical pressure fluid in a vertical heated tube is be featured as the following regimes: for the upward flow, from no-effect to slight enhancement, significant reduction, recovery and then enhancement; for the downward flow, from no-effect to slight weaken, and then enhancement. Moreover, the experimental results showed that $y^+|_{T_{f(r)}=T_{pc}} = 5$ is where there is an onset of heat transfer deterioration for the upward flow in a vertical heated tube induced by buoyancy effects. The results presented provide a better understanding of the special features of the turbulent convection heat transfer of supercritical pressure fluids in mini channels.

1. Introduction

Convection heat transfer of supercritical pressure fluid has been studied since the 1950s, due to the development of supercritical thermal and nuclear power stations [1–7]. The continuing and growing interest originates from fundamental problems that must be solved for the many practical systems with supercritical fluid applications. In the middle of the last century, supercritical pressure water ($T_c = 374.14$ °C, $P_c = 22.12$ MPa) was used as working fluid in supercritical thermal power plants. The supercritical pressure water cooled reactor (SPWR) was also proposed and studied. Carbon dioxide ($T_c = 31.05$ °C, $P_c = 7.38$ MPa) was chosen as the alternative fluid to study the heat transfer performance of supercritical pressure fluids since its supercritical state is much easier to obtain in the lab than water. With technology developments, power systems based on the supercritical CO_2 cycle have been in the spotlight. Due to the relatively compact size and high efficiency, the supercritical CO_2 Brayton cycle has been widely investigated for next-generation nuclear reactors [8] and concentrated solar power systems [9]. The supercritical pressure CO_2 can be also utilized in the Allam cycle for a fossil fuel thermal power system to increase efficiency [10]. In recent years, Carbon Capture, Utilization and Storage (CCUS) has been regarded as a new technology that can mitigate greenhouse gas emissions on a large scale. The flow

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Nomenclature

Bo^*	non-dimensional buoyancy parameter
c_p	specific heat at constant pressure [J/(kg K)]
d	tube diameter [m]
g	gravitational acceleration [m^2/s]
G	mass flux [kg/m^2 s]
Gr^*	Grashof number
h	bulk specific enthalpy [J/kg]
$h(x)$	local heat transfer coefficient [W/(m^2 K)]
Kv	non-dimensional flow acceleration parameter
Nu	Nusselt number
p	pressure [MPa]
Pr	Prandtl number
r	tube radius
Re	Reynolds number
T	temperature [°C]
y^+	dimensionless wall distance

Greek symbols

α_p	thermal expansion coefficient [1/K]
β_T	isothermal compression coefficient [1/Pa]
δ	tube wall thickness [m]
λ	thermal conductivity [W/(m K)]
μ	molecular viscosity [Pa s]
ρ	fluid density [kg/m^3]

Subscripts

f	fluid
pc	pseudo critical
w	wall

and thermal behavior of CO_2 in injection wells and target reservoirs is important to all CO_2 geological storage (CCS) and utilization technologies, including enhanced geothermal system with CO_2 (CO_2-EGS), CO_2 storage with gas recovery (CO_2-EGR), and enhanced oil recovery with CO_2 (CO_2-EOR) [11,12]. Meanwhile, the hydrocarbon fuels at supercritical pressures are used in thermal protection for rocket thrusters, high-performance aircraft and missile engines [13], etc. Therefore, the convection heat transfer of supercritical pressure fluid in recent times has received an increasing amount of attention.

The variation of thermal properties of the supercritical pressure fluid is sharp, especially near the pseudo-critical temperature: the specific heat rises and then decreases rapidly, and density and viscosity decrease sharply [15]. The effects of flow direction, heat flux, fluid temperature, and mass flow rate on the convection heat transfer of supercritical pressure fluid flowing inside vertical tubes are very complex, with different researchers presenting different results. Nevertheless, previous research has confirmed that there are three heat transfer regions for convection heat transfer of supercritical pressure fluid flowing inside vertical tubes [1–7,14–19]: (1) normal heat transfer region which can be characterized with heat transfer coefficients similar to those of subcritical convective heat transfer far from critical or pseudocritical regions, (2) heat transfer deterioration (HTD) region which is characterized with lower values of the heat transfer coefficient compared to those at the normal heat transfer region, and (3) heat transfer enhancement (HTE) region which is characterized with higher values of the heat transfer coefficient compared to those at the normal heat transfer region [15]. Research on the HTD phenomenon and the starting point of HTD has received continuous interest. The deteriorated heat transfer usually appears at higher heat fluxes and lower mass fluxes; therefore, the relationships between heat flux and mass flux were selected to estimate the starting point of the HTD. Some empirical correlations have been proposed in the literature [16,17] to calculate the critical heat flux for convection heat transfer of supercritical fluids, q_{HTD}. For the starting point prediction of the HTD for supercritical pressure CO_2, Shiralkar and Griffith [1] found that deteriorated heat transfer started at certain ratio of $q/G = 0.116$ and was affected with inlet temperature and direction of flow, where q is in kW/m^2 and G is in kg/m^2s. Kim et al. [18] proposed the ratio of $q/G^2 = 0.0002$. However, these correlations were obtained at various operating conditions and showed quite different prediction results. Moreover, these correlations were the fitting curves of the experimental results without revealing the deterioration mechanism.

Many researchers have confirmed that HTD may be caused by three reasons and some non-dimensional parameters have been defined to predict the onset of HTD: (1) The sharp variation of thermo-physical properties. (2) The effect of buoyancy force induced by radial non-uniform density distribution. Jackson and Hall [7] introduced a non-dimensional parameter, Bo^*, to evaluate the buoyancy influence on convection heat transfer behavior of fluids at supercritical pressures in vertical channels:

$$Bo^* = Gr^*/(Re^{3.425}Pr^{0.8}), \tag{1}$$

where Gr^* was calculated as

$$Gr^* = g\beta d^4 q_w/(\lambda_f \upsilon^2). \tag{2}$$

(3) the effect of thermal expansion and flow acceleration induced by variations of temperature and pressure in the axial direction under heating condition. McEligot and Jackson [19] proposed a non-dimensional parameter, Kv_T, to evaluate the influence of the thermal acceleration on convection heat transfer of supercritical pressure fluids:

$$Kv_T = \frac{4q_w d\alpha_p}{Re^2 \mu c_p} \tag{3}$$

When $Kv_T \geq 3 \times 10^{-6}$, for turbulent flow the turbulence may be significantly reduced and may even re-laminarise, resulting in the deterioration of convection heat transfer. Jiang et al. [22] proposed firstly a non-dimensional parameter, Kv_P, to evaluate the flow acceleration effect induced by the axial density variations due to the axial pressure decrease for convection heat transfer in a mini- or micro-tube:

$$Kv_P = -\frac{d}{Re}\beta_T\frac{dp}{dx}. \tag{4}$$

In recent years, experimental investigations on heat transfer of fluids at supercritical pressures have focused on turbulent convection heat transfer characteristics. Moreover, researchers have paid more attention to ways of enhancing heat transfer and inhibiting or weakening heat transfer deterioration. Jiang et al. [20–25] investigated the convection heat transfer of supercritical pressure carbon dioxide in vertical heated circular tubes with inner diameters of 2.0 mm, 1 mm, 0.27 mm, and 99.2 μm. They found that under the experimental conditions, for a tube with an inner diameter of 2.0 mm, the heat transfer deterioration is mainly caused by buoyancy effects; as the inner diameter reduced, the flow acceleration becomes the main factor that results in the abnormal heat transfer phenomenon, while the buoyancy effect