International Journal of Heat and Fluid Flow 32 (2011) 176–191

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Experimental investigation of heat transfer in vertical upward and downward supercritical CO_2 flow in a circular tube

Dong Eok Kim, Moo-Hwan Kim *

Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Namgu, Pohang, Kyungbuk 790-784, Republic of Korea

A R T I C L E I N F O

Article history:
Received 29 March 2010
Received in revised form 1 September 2010
Accepted 3 September 2010

Keywords:
Supercritical CO_2
Local heat transfer
Buoyancy
Flow acceleration
Correlation

A B S T R A C T

An experimental investigation of turbulent heat transfer in vertical upward and downward supercritical CO_2 flow was conducted in a circular tube with an inner diameter of 4.5 mm. The experiments were performed for bulk fluid temperatures from 29 to 115 °C, pressures from 74.6 to 102.6 bar, local wall heat fluxes from 38 to 234 kW/m^2, and mass fluxes from 208 to 874 kg/m^2 s. At a moderate wall heat flux and low mass flux, the wall temperature had a noticeable peak value for vertical upward flow, but increased monotonically along the flow direction without a peak value for downward flow. The ratios of the experimental Nusselt number to the value obtained from a reference correlation were compared with Bo^* and q^+ distributions to observe the buoyancy and flow-acceleration effects on heat transfer. In the experimental range of this study, the flow acceleration predominantly affected the heat-transfer phenomena. Based on an analysis of the shear-stress distribution in the turbulent boundary layer and the significant variation of the specific heat across the turbulent boundary layer, a new heat-transfer correlation for vertical upward and downward flow of supercritical pressurized fluid was developed; this correlation agreed with various experimental datasets within ±30%.

1. Introduction

Supercritical fluids have been drawing attention as heat-transfer media for power plant technology and for refrigeration and air-conditioning applications. The heat-transfer characteristics of supercritical fluids are key parameters for these system applications. In particular, heat transfer at supercritical pressure is influenced by the significant changes in thermophysical properties (thermal conductivity, density, viscosity, specific heat, volume expansion coefficient, etc.). Near the critical point, the physical properties of fluids vary rapidly with temperature and pressure (Fig. 1a–f), so heat transfer at supercritical pressure is totally different from that at subcritical pressure. The pseudo-critical temperature (T_{pc}) is a temperature point at which the specific heat of a fluid at a critical pressure reaches a peak value. In most heat-transfer phenomena, the diffusion of heat (by both molecular and turbulent motion) can be significantly affected by variations of thermal conductivity, specific heat, and viscosity with temperature (Eq. (1)) (Winterton, 1998).

$$Nu_b = \frac{hD}{k_b} = 0.023\mathrm{Re}_b^{0.8}\mathrm{Pr}_b^{0.4}$$
$$h = 0.028\dot{m}^{0.8}D^{-1.8}\mu_b^{-0.4}k_b^{0.6}c_{p,b}^{0.4}. \qquad (1)$$

In internal heat-transfer phenomena near the thermodynamic critical point, the physical properties of fluids vary significantly both across and along the fluid flow direction. In particular, severe variations in density between bulk and wall positions and along the flow direction can change the flow structure and affect the turbulence in the flow due to the influences of buoyancy and flow acceleration. This change in turbulence in turn affects the rate of heat transfer by turbulent energy transport. When the buoyancy and flow-acceleration effects are extreme, the velocity profile at a cross-sectional area of the flow can change from a parabolic shape to an 'M' shape (see Fig. 2) (Kurganov and Zeigarnik, 2005). This change of flow structure can significantly affect the turbulent shear-stress distribution and turbulent eddy diffusivity. Eventually, a change in the turbulent flow structure can exert a strong influence on the turbulent heat-transfer phenomena.

McEligot et al. (1970) 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 (1971) tried to present a physical mechanism for the local deterioration in the heat-transfer coefficient of supercritical fluid flow. He reported that the turbulent diffusivity was reduced in upward flow when the low density layer became thick enough to reduce the shear stress in the region where energy is normally fed into the turbulence, and that this reduced the diffusivity for heat and thus the heat-transfer coefficient. Tanaka et al. (1973)

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* Corresponding author.
E-mail address: mhkim@postech.ac.kr (M.-H. Kim).

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doi:10.1016/j.ijheatfluidflow.2010.09.001

Nomenclature

A_{in}	area of the test tube inner surface (m^2)
Bo^*	buoyancy parameter, $Bo^* = \mathrm{Gr}_q/(\mathrm{Re}_b^{3.5}\mathrm{Pr}_b^{3.5})$
c_p	specific heat at constant pressure (kJ/kg K)
$\overline{c_p}$	mean specific heat (kJ/kg K), $(i_w - i_b)/(T_w - T_b)$
D	tube diameter (m)
$f\,[\,]$	function of
G	acceleration of gravity (m/s^2)
Gr_q	Grashof number based on heat flux, $g\beta_b D_{in}^4 q''_w/(v_b^2 k_b)$
h	heat-transfer coefficient (W/m^2 K)
i	enthalpy (kJ/kg)
k	thermal conductivity (W/mK)
k_s	thermal conductivity of solid material (W/mK)
K_v	flow-acceleration parameter, $4q''_w D_i/(\mathrm{Re}_b^2 \mu_b c_{p,b} T_b)$
L	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, hD/k
P	pressure (bar)
Pr	Prandtl number, $c_p\mu/k$
q''_w	local wall heat flux (W/m^2)
q''_{loss}	local loss heat flux (W/m^2)
q^+	non-dimensional heat flux, $q''_w\beta_b/(Gc_{p,b})$
$\dot{q}$	volumetric heat generation rate (W/m^3)
Q	total heat-transfer rate (W)
R	gas constant (kJ/kg K)
Re	Reynolds number, $4\dot{m}/(\pi D\mu)$
r	radial coordinate (m)
T	temperature (°C or K)
u	mean velocity of flow (m/s)
x	axial distance (m)

Greek symbols

β	volume expansion coefficient ($1/K$)
δ	boundary layer thickness (m)
δ^+	non-dimensional boundary layer thickness
μ	dynamic viscosity (Pa s)
v	specific volume (m^3/kg)
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
cr	critical
i, in	inner, inlet
o	outer
pc	pseudo-critical
w	evaluated at wall

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 upon the shear-stress gradient at the wall, they deduced criteria for the prominent effects of buoyancy and acceleration. Petukhov et al. (1972) investigated experimentally the worsening heat-transfer conditions for CO_2 turbulent flow at supercritical pressure. In their experiments, at low and moderate mass flow rates, the local worsening of heat transfer was clearly observed, but at a high mass flow rate, no worsening of the local heat transfer occurred. To obtain criteria to describe the start of deteriorated 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. Yamagata et al. (1972) proposed a heat-transfer correlation that predicted the enhanced heat-transfer coefficients near the pseudo-critical point at low and moderate heat fluxes reasonably well, and the limit of heat flux for the occurrence of heat-transfer deterioration. Jackson and Hall (1979) investigated the influences of buoyancy on heat transfer to 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 (1993) studied experimentally the velocity and temperature fields in a supercritical CO_2 flow through a heated vertical circular tube. Making use of experimental results and integral equations of continuity, energy, and motion, they determined profiles for the shear stress, heat flux, gradient coefficients of the heat and momentum eddy diffusivities, and turbulent Prandtl number. 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. Liao and Zhao (2002) investigated the convection heat transfer to supercritical CO_2 in heated horizontal and vertical miniature tubes. In their downward flow experiments, significant heat-transfer impairment was observed in the pseudo-critical region. Fewster and Jackson (2004) introduced a simple semi-empirical heat-transfer model of fully developed mixed convection in vertical tubes. The model predicted the development of impaired heat transfer with an increase of buoyancy influence for upward flow, followed by recovery and enhancement. Systematic enhancement of the heat transfer for downward flow was observed. Jiang et al. (2008) investigated experimentally and numerically convection heat transfer of supercritical CO_2 in a 0.27-mm-diameter vertical mini-tube. Their results indicated that the flow direction, buoyancy, and flow acceleration had little influence on the local wall temperature. He et al. (2005) 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 be significantly impaired as a result of flow acceleration when the heating was strong, which caused a reduction in turbulence production. Bazargan and Mohseni (2009) focused on the significance of the buffer zone in the boundary layer. Their results showed that in the enhanced heat-transfer regime, the heat-transfer coefficient peak occurred when the pseudo-critical temperature, or the maximum heat capacity, was located within the buffer layer. They also reported that in the deteriorated heat-transfer regime, the extent of the laminar sublayer appeared to be changed so that the buffer zone was farther away from the wall.

Several heat-transfer correlations for the fluid flow at supercritical pressure have been proposed (McAdams et al., 1950; Bringer and Smith, 1957; Miropolsky and Shitsman, 1967; Krasnoshchekov and Protopopov, 1959; Petukhov et al., 1961; Domin, 1963; Kutateladze and Leontiev, 1964; Bishop et al., 1965; Swenson et al., 1965; Touba and McFadden, 1966; Kranoshchekov and Protopopov, 1966; Yamagata et al., 1972; Miropolsky and Pikus, 1967; Lokshin et al., 1968; Schnurr, 1969; Dashevskiy et al., 1987; Liao and Zhao, 2002; Fewster and Jackson, 2004; Kuang et al., 2008; Bae and Kim, 2009); most were developed by combining existing