International Journal of Heat and Mass Transfer 126 (2018) 201–210

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Influence of channel scale on the convective heat transfer of CO_2 at supercritical pressure in vertical tubes

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ARTICLE INFO

Article history:
Received 28 August 2017
Received in revised form 13 April 2018
Accepted 17 April 2018

Keywords:
Supercritical pressure
Convective heat transfer
Channel scale
Buoyancy
Flow acceleration

ABSTRACT

Channel scales vary from several centimeters to several micrometers in various industrial applications that conduct convective heat transfer at supercritical pressures. The heat transfer performance reveals relatively different features even under similar Reynolds number and thermphysical property conditions. The authors investigated the influence of the channel scale on the supercritical convective heat transfer based on the experimental results conducted on vertical tubes with inner diameters of 0.27 mm and 2.0 mm. Numerical simulations using several low Reynolds number k-ε turbulence models were also discussed to evaluate the performance of turbulence models when modelling supercritical heat transfer in tubes of various scales. The results exhibited significant heat transfer deterioration due to flow acceleration effect in the 0.27 mm tube at a heat flux to mass flux ratio of about 0.2, whereas the 2.0 mm tube at a similar inlet Reynolds number and heat flux to mass flux ratio exhibited great heat transfer enhancement due to the buoyancy effect. The heat transfer deterioration in the 0.27 mm tube can be explained by its relation to the redistributed mean velocity profiles and the relatively small energy-containing scale while relatively large dissipation scale as compared to those in the 2.0 mm tube.

1. Introduction

Convective heat transfer to fluids flowing in channels at supercritical pressures is a basic yet important heat transfer problem that is present in extensive industrial applications that operate with working fluids at supercritical pressures such as in transcritical CO_2 systems, CO_2 utilization and storage technologies, supercritical fluid extraction (SFE) units, platelet transpiration cooling technology, supercritical water oxidation technology. It is especially important in the power generation systems including the solar thermal system [1], the fossil fuel power plant [2], and the nuclear power system such as in the supercritical pressure water-cooled reactor (SCWR) [3], wherein the thermal efficiency is increased and the supercritical fluids do not experience phase changes, thereby avoiding a boiling crisis.

Although the geometry is relatively simple, the heat transfer characteristics can be very complex due to the sharp thermophysical properties induced by small fluid temperature variations as presented in Fig. 1 [4], which affect the heat transfer in two kinds of mechanisms, namely the direct and indirect one. The former exclusively attributes to the thermophycal properties that directly affect heat transfer and can be accurately predicted by several earlier supercritical heat transfer correlations, such as that proposed by Krasnoshchekov and Protopopov [5] (KP correlation for short) and the correlation modified by Jackson based on the KP correlation [6]. The latter was generally divided into two subcategories, namely the flow acceleration effect and the buoyancy effect, which were induced by the redistributed flow field due to the non-uniform density variation in the axial and radial direction, respectively, thereby indirectly affecting heat transfer.

The channel scale is one of the main parameters that affect the supercritical pressure heat transfer characteristics. Especially, the significance of the flow acceleration and buoyancy effects are different in channels of different scales in the industrial applications of supercritical pressure fluids. For example, the flowing channels in the reactor core of the supercritical water-cooled reactor (SCWR) are roughly 2.5–3.0 mm in diameter and the mini-channel heat exchanger flow channels in the transcritical CO_2 refrigeration systems are smaller than 1.0 mm, whereas the flow passages in the platelet transpiration cooling structures of the rocket thruster are several micrometers in diameter. The flow acceleration and

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.080
0017-9310/

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, $=\beta g d^4 q_w/(\lambda \upsilon^2)$
h	bulk specific enthalpy [J/kg]
L	energy containing scale or heated length [m]
k	turbulent kinetic energy [m^2/s^2]
M	molecular weight [kg/mol]
Nu	Nusselt number
Nu_f	Nusselt number for forced convection
Kn	Knudsen number
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	tube radius [m] or universal gas constant
Re	Reynolds number, $=ud/\upsilon$
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]
y	distance from the wall in the normal direction [m]
y^+	non-dimensional distance from the wall, $y^+ = \frac{y}{\upsilon}\sqrt{\tau_w/\rho}$

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)] or mean free path [m]
μ	dynamic viscosity [Pa·s]
μ_t	turbulent dynamic viscosity [Pa·s]
η	dissipation scale (Kolmogorov scale) [m]
υ	kinematic viscosity [m^2/s]
υ_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

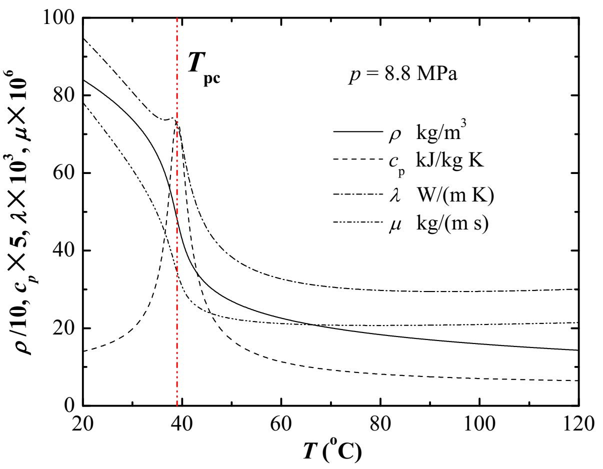

Fig. 1. CO_2 properties at supercritical pressures [4] (p = 8.8 MPa).

buoyancy effects on the supercritical heat transfer in channels of different scales have been qualitatively reported by previous researchers. Kurganov et al. [7] identified the importance of the flow acceleration effect only in small diameter tubes while large diameter tubes characterized buoyancy as the main factor. Li et al. [8,9], Xu et al. [10–11] and Jiang et al. [12–16] have investigated the supercritical pressure heat transfer of CO_2 or Freon flowing through vertical tubes with inner diameters of 2.0 mm [8,9,13], 0.953 mm [10–12], 0.27 mm [14,15], and 0.0992 mm [16] in various test conditions. The buoyancy and flow acceleration effects have been respectively evaluated for each channel scale based on the experimental results. The general trends were consistent with the results reported by Kurganov et al. [7]. However, the quantitative comparisons of buoyancy and flow acceleration effects among tubes at different diameters have been minimally reported. Additionally, the integral performance of heat transfer between facilities at different scale is important when defining a link between the experimental results at various operating conditions and the prototypic conditions in the real applications. Song et al. [17] proposed a mathematical scaling criterion for the similarity of integral heat transfer in terms of the length to diameter ratio, L/D, and wall heat flux to mass flux ration, q_w/G based on the experimental data of supercritical heat transfer of CO_2 in vertical tubes at different diameters of 4.4 and 9.0 mm. They also claimed that at the same enthalpy both the amount of fluid packet and the wall temperature can change depending on the mode of heat transfer, and both normal heat transfer mode and deteriorated heat transfer mode are possible at the same bulk flow enthalpy. However, the different heat transfer mode at the same bulk flow enthalpy and the detailed mechanism has not been further reported.

In another respect, Computational Fluid Dynamic (CFD) modeling has been regarded as a method helping understand the phenomenon and mechanisms of supercritical heat transfer. Previous numerical investigations mainly focused on the buoyancy-deteriorated heat transfer in vertical tubes with relatively large diameters (>2.0 mm), such as He et al. [18], Xiong and Cheng [19], Mohseni and Bazargan [20], Zhao et al. [21], Bae et al. [22]. The performance of various turbulence models, including the k-ω SST turbulence model, standard and low Reynolds number k-ε tur-