International Journal of Heat and Mass Transfer 125 (2018) 274–289

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

The buoyancy force and flow acceleration effects of supercritical CO_2 on the turbulent heat transfer characteristics in heated vertical helically coiled tube

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ARTICLE INFO

Article history:
Received 6 January 2018
Received in revised form 9 March 2018
Accepted 8 April 2018

Keywords:
Supercritical CO_2
Helically coiled tube
Semi-empirical correlation
Buoyancy force
Flow acceleration

ABSTRACT

Numerical simulations are performed to investigate the turbulent heat transfer characteristics of supercritical CO_2 in heated vertical helically coiled tube, and primary focus is to analyze the mechanism of buoyancy force and flow acceleration on the heat transfer. The results show similar effect from buoyancy force and centrifugal force, and both forces induce a secondary flow in the cross section that improves the heat transfer efficiency. The buoyancy parameter ϕ^2 and flow acceleration parameter q^+ are established with reasonably good validation against numerical results. On the basis of the two parameters, the buoyancy factor F_b and the acceleration factor F_{Ac} are proposed to quantify buoyancy and flow acceleration effect, respectively. Furthermore, a temperature difference correction factor F_t is introduced to consider variation of thermo-physical properties. A new semi-empirical heat transfer correlation is proposed for supercritical CO_2 in function of F_b, F_{Ac} and F_t for the vertical helically coiled tube.

1. Introduction

Carbon dioxide (CO_2) is considered as one of the most potential natural working materials because of its advantageous features such as ODP (Ozone Depletion Potential) = 0, GWP (Global Warming Potential) = 1, non-flammability and non-toxicity as an environment friendly working fluid. In addition, CO_2 has a relatively low critical temperature and pressure compared to water. Supercritical CO_2 systems, such as Organic Rankine cycle (ORC) and combined cooling, heating, and power system (CCHP) [1,2], has been used in the production of modern industry, and expectation is beneficial to settling the increasingly serious environmental problems [3]. The heat transfer of supercritical CO_2 in helically coiled tubes (HCTs) are widely adopted in heat pump air-conditioning systems, low-grade waste heat recovery, due to its compact structure and better heat transfer performance than straight tube [4]. Therefore, study on the heat transfer characteristics of supercritical CO_2 in HCT is of great significance in heat exchangers design.

As shown in Fig. 1, the thermo-physical properties of supercritical CO_2 at 8.0 MPa undergo dramatically change over a narrow temperature range near the pseudo-critical region. Compared to sub-critical fluid, the special feature of supercritical fluid is its transit from liquid-like to gas-like in a sequential manner without encountering boiling. The non-uniform distribution of density in the cross-section and thermal expansion due to the reduction of density generate buoyancy force effect and flow acceleration effect, which will significantly influence heat transfer.

In the earlier study, many researchers had explored the characteristics of heat transfer and flow of supercritical fluid in vertical tubes [5–13]. T Hiroaki et al. [5] theoretically analyzed the heat transfer mechanism of supercritical fluid in heated vertical tube and found that heat transfer deterioration stems from the reduction of shear stress due to buoyancy force and flow acceleration. The criteria for onset of buoyancy and acceleration effect were developed with the assumptions of uniform velocity acceleration profile and similar effect between buoyancy and acceleration effects. Experimental and theoretical investigation on the buoyancy and acceleration effect of supercritical fluid in vertical straight tube was performed by Jackson [6], and presented three semi-empirical models with consideration of buoyancy effect, acceleration effect and their interaction them. A strong buoyancy effect changes the velocity profile from 'U' shape to 'M' shape [7]. A strong flow acceleration effect causes the relaminarization of turbulent boundary layer, which eventually deteriorates heat transfer performance due to reduced intensity of turbulence [8,9]. Negoescu et al. [10] numerically investigated the heat transfer behavior of supercritical nitrogen in a heated vertical mini tube,

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.033
0017-9310/

Nomenclature

ϕ	buoyancy parameter of helically coiled tube
q^+	non-dimensional heat flux or acceleration parameter
Bo, Bu, Bo^*	buoyancy number
Gr	Grashof number
Gr^*	Grashof number based on uniform heat flux
Nu	Nusselt number
q^+	acceleration parameter
Re	Reynolds number
Fr	Froude number
De	Dean number
De^*	modified Dean number
$\overline{Pr}$	modified Prandtl number
Pr_t	turbulent Prandtl number
Pr	Prandtl number
F_b	buoyancy factor thickness
F_{Ac}	acceleration factor
F_t	temperature difference modified factor
a	inner pipe radius [mm]
b	coil pitch divided by 2π [mm]
c_p	specific heat [J/(kg·K)]
$\overline{cp}$	modified specific heat [J/(kg·K)]
D	curvature diameter [mm]
d	tube diameter [mm]
g	gravitational acceleration [m/s^2]
G	mass flux [$kg/(m^2 \cdot s)$]
h	heat transfer coefficient [$W/(m^2 \cdot K)$]
L	tube length [mm]
P	Pressure [MPa]
q_w	heat flux [W/m^2]
T	temperature [K]
i	specific enthalpy [J/kg]
u	velocity [m/s]
$\overline{u}$	mean velocity [m/s]
f	friction factor
x	dimensional axial coordinate
f_b, f_c	buoyancy force, centrifugal force [N]
K	kinetic energy [m^2/s^2]
W	specific work [W]

r	dimensional radial coordinate
$y+$	non-dimensional distance

Greek symbols

τ	shear stress
γ	non-dimensional torsion
δ	boundary layer thickness
v	kinematic viscosity [m^2/s]
μ	dynamic viscosity [Pa·s]
λ	thermal conductivity [W/(m·K)]
ρ	density [kg/m^3]
$\overline{\rho}$	modified density [kg/m^3]
β	volume expansion coefficient [K^{-1}] or helical angle [°]
φ	dimensional circumferential coordinate
δ^+	dimensionless boundary-layer
Γ	diffusion coefficient of energy
α	inclined angle
σ	x/L
ϖ	non-dimensional curvature

Subscripts

a	axial
b	bulk or buoyancy
w	wall
c	centrifugal or based on helically coiled
up	upward
$down$	downward
ra	radial
cri	critical
ng	no-gravity
Ac	acceleration
t	temperature
bu	buoyancy
ac	acceleration
pc	pseudo-critical

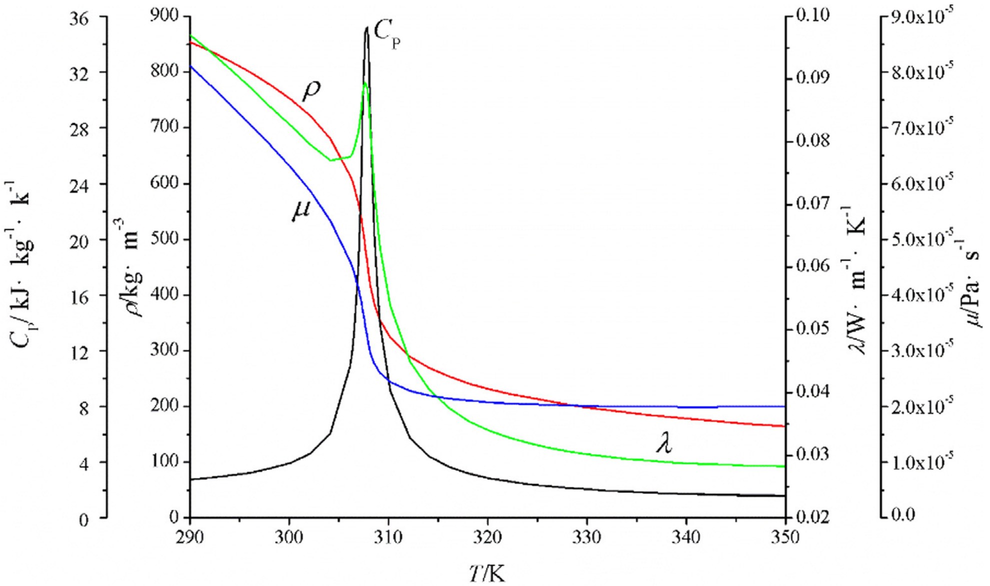

Fig. 1. Thermal physical properties of supercritical CO_2 fluid at 8.0 Mpa.