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Experimental and numerical investigation on heat transfer characteristics of supercritical CO_2 in the cooled helically coiled tube

Kai-Zheng Wang[a], Xiao-Xiao Xu[a,*], Chao Liu[a], Wan-Jin Bai[b], Chao-bin Dang[c]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, No. 174 Shazhengjie, Shapingba, Chongqing 400044, PR China
[b] School of Mechanical and Automotive Engineering, Chongqing Jiaotong University, No. 66 Xuefu road, nan'an, Chongqing 400074, PR China
[c] Department of Human and Engineered Environmental Studies, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8563, Japan

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ABSTRACT

The heat transfer characteristics of supercritical CO_2 cooled in the helically coiled tube are investigated experimentally and numerically. The inner diameter, coil pitch and coil radius of the helically coiled tube are 4 mm, 34 mm and 36 mm, respectively. The effects of heat flux, pressure and mass flux on the heat transfer are analyzed based on 512 sets of experimental data, a new modified correlation is developed to calculate the heat transfer coefficients of supercritical CO_2 in the cooled helically coiled tube. To study the buoyancy effect, the heat transfer coefficients of upward flow are compared to that for horizontal flow, and it is found that the effect of buoyancy is negligible in the liquid-like region, but significant in other region under the experimental conditions. On this basis, the three buoyancy parameters: Bu_p, Gr_{th}/Gr_q and Ri are applied to predict the effect of buoyancy on the heat transfer. The three parameters overestimate the impact of buoyancy. Numerical analysis of the cooling heat transfer coefficient in helically coiled tube is conducted by using shear-stress transport (SST) model. The flow fields are analyzed and the effect of heat flux is mainly related to the distribution of specific heat (c_p) in the radial direction of tube transverse section.

1. Introduction

As an environmentally friendly, nontoxic and nonflammable refrigerant, carbon dioxide (CO_2) offers attractive thermal characters such as small viscosity and large refrigerant capacity. Supercritical CO_2 has been widely applied in heat pumps, nuclear reactors and aerospace engineering [1–3]. In heat pumps, the helical-coil-in-fluted-tube gas cooler attracts much attention due to the compact-sized, high heat exchanging efficiency and avoiding cross contamination [4]. However, the little investigation on the heat transfer characteristics and mechanism for supercritical CO_2 in the helical-coil-in-fluted-tube gas cooler is openly published.

Many investigations have concentrated on the heat transfer characteristics of supercritical CO_2 in straight tubes [5–7]. Dang and Hihara [8] conducted analysis on the effects of heat flux, mass flux and pressure on heat transfer of supercritical CO_2 cooled in the horizontal circular tube. Results showed that the heat transfer coefficient decreases with the increase of heat flux at pseudocritical temperature region. However, the heat transfer coefficients decrease slightly with the increase of heat flux at gas-like region. Oh and Son [5] performed experiments on the heat transfer of supercritical CO_2 in circular tubes. In order to develop a more accurate heat transfer correlation, the region was divided into two parts ($T_b < T_{pc}$ and $T_b > T_{pc}$: T_b is the bulk temperature and T_{pc} is the pseudo-temperature). Experimental results were obtained by constant wall temperature [9]. They concluded that the buoyancy affects the heat transfer significantly and the buoyancy effect was included in the heat transfer correlations. Liu et al. [10] investigated the heat transfer of supercritical CO_2 cooled in the large diameter tube. Forooghi and Hooman [11] performed experimental investigation on the heat transfer characteristics in plate heat exchanger, the radial distribution of properties affects the heat transfer significantly.

Bruch et al. [12] conducted experiments on heat transfer in cooled vertical tube. They found that the buoyancy effect mainly exists in the liquid-like region and the pseudo-critical region. There were many literatures in which the criteria were used to predict the effect of buoyancy on the heat transfer in past few years. The buoyancy parameter, $\overline{Gr}/Re_b^{2.7} = 1 \times 10^{-5}$ proposed by Jackson and Hall [13] was applied [14] to evaluate the buoyancy effect on the heat transfer in vertical upward annuli. Liao [15] adopted $Gr/Re_b^2 = 0.001$ (proposed by Kakac [16]) to predict the effect of

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* Corresponding author.
E-mail address: xuxiaoxiao@cqu.edu.cn (X.-X. Xu).

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Nomenclature

a	inner pipe radius [m]
b	coil pitch divided by 2π [m]
Bo^*	Buoyancy number
Bu	Buoyancy parameter
c_p	specific heat [J kg^{-1} K^{-1}]
$\overline{c_p}$	modified specific heat [J kg^{-1} K^{-1}]
D	curvature diameter [mm]
d	tube diameter [mm]
g	gravitational acceleration [m s^{-2}]
G	mass flux [kg m^{-2} s^{-1}]
Gr	Grashof number
h	heat transfer coefficient [W m^{-2} K^{-1}]
i	specific enthalpy [J kg^{-1}]
l	tube length
$LMTD$	logarithmic mean temperature difference
m	mass flow rate [kg s^{-1}]
Nu	Nusselt number
p	Pressure [MPa]
Pr	Prandtl number
$\overline{Pr_b}$	modified Prandtl number
q	heat flux [W/m^2]
Q	heat capacity [W]
Re	Reynolds number
Ri	Richardson number
T	temperature [°C]

Greek symbols

β	volume expansion coefficient [K^{-1}]
λ	thermal conductivity [W m^{-1} K^{-1})]
μ	dynamic viscosity [Pa s]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]

Subscripts

b	bulk
c	centrifugal
cal	calculation
cu	copper
exp	experimental data
film	film temperature
g	gravitational
p	Petukhov
pc	pseudo-criticalpoint
i	inside/number
in	inlet
o	outside
out	outlet
w	wall
water	water

buoyancy in horizontal circular tube. The buoyancy parameters: $Bo^* = \overline{Gr}/(Re_b^{3.5} + Pr_b^{0.8}) = 5.6 \times 10^{-5}$ [17] and $Gr/Re_b^2 = 0.001$ were employed to present the effect of buoyancy in microtubes. The buoyancy parameter $Gr/Re^2 = 0.1$ cannot predict the buoyancy effect on the heat transfer of supercritical fluids [18]. Inversely, the buoyancy parameter, $Gr_{th} = Gr_q$ [19] predicted the effect of buoyancy accurately. Bae et al. [20] and Yu et al. [21] experimentally investigated the effect of buoyancy on the heat transfer of supercritical water in the horizontal tube. When the heat transfer deterioration appeared, they found that $Gr/Re_b^2 = 0.001$ and $Gr_{th} = Gr_q$ were inadequate for predicting the effect of buoyancy effectively. Tanimizu and Sadr [22] used three buoyancy parameters, $Gr/Re_b^2 = 0.001$, Bo_j and $Bu_p = 3 \times 10^{-5}$ for predicting the buoyancy effect. The variation of the three buoyancy criteria did not accord with the trend of heat transfer along the pipe. In conclusion, the buoyancy criteria performed differently at different conditions. However, the study of buoyancy effect on the heat transfer of supercritical CO_2 cooled in helically coiled tube is little.

Few researches focused on the heat transfer of supercritical fluids in helically coiled tubes. Zhang et al. [23] conducted experiments on the heat transfer characteristics of supercritical CO_2 heated in vertical helically coiled tube with an inner diameter of 9 mm and developed correlations for heat transfer coefficients. Wang et al. [24] numerically investigated the heat transfer characteristics of supercritical CO_2 heated in the vertical helically coiled tube. Zhang et al. [23] only focused on the heat transfer characteristics of supercritical CO_2 heated in the vertical helically coiled tube.

The heat transfer characteristics and mechanism of supercritical CO_2 in the cooled helically coiled tube is still deficient. In this paper, the experimental and numerical investigations are carried out on the heat transfer of supercritical CO_2 in the helically coiled tube. The effects of mass flux, heat flux, pressure and buoyancy on the heat transfer are analyzed. The three buoyancy parameters in predicting the effect of buoyancy on the heat transfer are assessed. A modified correlation is proposed to predict the heat transfer coefficients of supercritical CO_2 cooled in the helically coiled tube. Further numerical analysis on the flow field is needed to understand the heat transfer mechanism.

2. Experiments

2.1. Experimental test facility

As is shown in Fig. 1, the experimental system includes a low temperature thermostat bath, a refrigerant pump, a mass flow meter, a pre-heater, a test section and a syringe pump. The subcooled CO_2 is collected in the liquid receiver, and then is fed to the preheater by a refrigerant pump. The mass flow rates of supercritical CO_2 are measured by a Coriolis type mass flow meter. After pre-heater, the CO_2 flows into the test section. Finally, the CO_2 is cooled by low temperature thermostat bath.

Fig. 2 shows the test points of test section. CO_2 flows inside the inner tube which is cooled by water in the annulus. The inner tube is made of copper and the outer tube is made of acrylic resin. Asbestos are wrapped on the test section to eliminate the effect of circumstance. Fig. 3 shows the schematic geometry of the helically coiled tube. The helically coiled tube is made of copper with 560 mm long, an inner diameter of 4 mm, an outer diameter of 6 mm, a coil pitch $2\pi b$ of 34 mm and a coil radius of 36 mm. Table 1 lists the accuracy of main measuring instruments.

2.2. Data reduction and experimental condition

The heat transfer coefficient is calculated by the following equation.

$$h = \frac{q}{LMTD} \tag{1}$$

The heat flux, q, is calculated by Eq. (2):