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Research Paper

Numerical study of the heat transfer to carbon dioxide in horizontal helically coiled tubes under supercritical pressure

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HIGHLIGHTS

- Centrifugal Richardson number increases with increase of fluid temperature.
- The Nusselt number correlations are presented with a high accuracy.
- Pressure is affected by fluid temperature after pseudo-critical temperature.
- Pressure difference has the minimum values in pseudo-critical temperature region.
- The wall temperature and h close to inner region are lower than other regions.

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ABSTRACT

The cooling heat transfer and pressure drop characteristics of supercritical CO_2 in the horizontal helically coiled tube are numerically simulated using RNG $k-\varepsilon$ turbulent model. The results show that the heat transfer coefficient and pressure drop in the helically coiled tube are larger than that in the straight tube because of the secondary flow. The heat transfer coefficient and pressure drop increase with the increase of mass flux and the peak value of heat transfer coefficient is shifted to high temperature region with the increase of pressure. The gravitational Richardson number decreases with the increase of the mass flux and the centrifugal Richardson number increases with the fluid temperature and mass flux increasing. The Nusselt number correlations are presented by using the numerical simulation values. The pressure distribution in helically coiled tube fluctuates from top to bottom like a wave because of the gravitational buoyancy force. When the fluid temperature is higher than the pseudo-critical temperature, the pressure is mainly affected by the fluid pressure and when the fluid temperature is lower than the pseudo-critical temperature, the pressure is mainly affected by the fluid temperature. The static pressure difference has the minimum values in the pseudo-critical temperature region. The wall temperature and the heat transfer coefficient close to the inner region are lower than the other regions.

1. Introduction

CO_2 is very friendly to the environment and it has the advantages of one global warming potential and zero ozone depletion potential. The critical temperature CO_2 is 31.1 °C and close to the ambient temperature. The systems with CO_2 operating at ambient temperature are likely to work close to the critical pressure of 7.38 MPa.

The heat transfer of heating and cooling of supercritical CO_2 in the tube has been studied a lot for a long time. Tanaka et al. [1] first measured the heat transfer coefficient of supercritical CO_2 under cooling condition in 1967. Krasnoshchekov et al. [2], Baskov et al. [3], Petrov and Popov [4,5] respectively obtained the calculation formula of heat transfer coefficient of supercritical CO_2 under cooling condition according to the experimental values.

Pitla et al. [6–9] used numerical simulation methods to study cooling convection heat transfer of supercritical CO_2 in the horizontal straight tube with the length of 1.8 m and the inner diameter of 4.7 mm. According to the numerical values the heat transfer correlation was proposed.

Liao and Zhao [10] experimentally investigated the convective heat transfer of supercritical CO_2 in horizontal and vertical tube. They found that despite *Re* had reached 10^5, buoyancy still had an important influence on convective heat transfer of supercritical CO_2. So the *Gr* was introduced to the heat transfer correlation by fitting the experimental data.

Dang et al. [11] experimentally investigated the heat transfer coefficient and pressure drop of four horizontal tubes under

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Nomenclature

a	tube radius [mm]
A	surface area [m^2]
b	coil pitch divided by 2π [mm]
Bo	buoyancy number
c_p	specific heat at constant pressure [J/(kg K)]
d	tube diameter [mm]
E	flow energy [W/kg]
f	friction factor
g	acceleration due to gravity [m/s^2]
G	mass flux [kg/(m^2 s)]
h	heat transfer coefficient [W/(m^2 K)]
k	turbulence kinetic energy [m^2/s^2]
L	length [mm]
Nu	Nusselt number
p	pressure [Pa]
P	coil pitch [mm]
Pr	Prandtl number
q	heat flux [W/m^2]
Gr	Grashof number
R	curvature radius [mm]
Re	Reynolds number
Ri	Richardson number
T	temperature [K]
u	velocity [m/s]
x	Cartesian coordinates [m]
y^+	non-dimensional distance from wall

Greek symbols

δ	curvature ratio [r/R]
θ	local polar coordinates in the cross-section [°]
λ	thermal conductivity [W/(m K)]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
τ	shear stress [N/m^2]

Subscripts

c	centrifugal force
cal	calculation result
cr	critical
d	dynamic
f	flow fluid
g	gravity
hc	helically coiled
i, j, k	general spatial indices
pc	pseudo-critical
s	straight
sta	static
sim	simulation result
t	total
w	wall

cooling conditions. The effect of mass flux, pressure, and heat flux was measured and the correlation was proposed on the basis of the form of Gnielinski correlation [12] using the experimental data.

Jiang et al. [13] studied the convective heat transfer of supercritical CO_2 using experimental and numerical method in vertical micro channel and they found that the effect of flow direction, buoyancy and self-acceleration on the wall temperature was not big. The heat transfer coefficient increased with heat flux increasing and then decreased with further increase in the heat flux for both upward and downward flows. Jiang et al. [14] also found that when the heat flux was relatively large, the buoyancy effect was very low. However, the acceleration caused by the buoyancy affected the turbulent kinetic energy and made the heat transfer coefficient become smaller in the large heat flow rate.

Yang et al. [15] studied the cooling heat transfer of supercritical CO_2 using numerical method in the straight tube. Seven different tilt angles of tube were studied and they found that the horizontal straight tube had the best heat transfer effect. Du et al. [16] simulated the cooling heat transfer of the supercritical CO_2 by numerical method in horizontal straight tube with diameter 6 mm, and found that almost all of the turbulence models could simulate cooling heat transfer of the supercritical CO_2 in a straight tube.

Many scholars also studied the convective heat transfer in helically coiled tube. Liberto and Ciofalo [17] studied turbulent heat transfer of water in the helically coiled tube using numerical simulation and found that turbulent intensity and heat transfer were stronger near the outside of the helically coiled tube. Lin and Ebadian [18] studied the effect of inlet turbulence intensity on the turbulent kinetic energy, the friction factor and heat transfer in the helically coiled tube and water was the working fluid. MAO et al. [19] studied mixed convective heat transfer experimentally of the subcritical and supercritical water in the helically coiled tube and found that when the Reynolds number was large enough, heat transfer coefficients in the helically coiled tube were close to those in the straight tube.

Wang et al. [20,21] experimentally studied the supercritical CO_2 flowing upward through the helically coiled tube under constant heat flux conditions. It was found that the inner wall temperatures and heat transfer coefficients were determined by the combined effects of physical property variation, buoyancy force and centrifugal force. The inner wall heat flux and mass flux had significant effects on fluid flow characteristics. Zhang et al. [22] also studied this model and they used the value of Bo to define the condition of the heat transfer. Xu et al. [23] simulated this model by numerical method. They found that the larger axial velocities appeared at the outer-bottom location; the higher wall temperatures appeared at the inner-top location and the outer-bottom locations hold larger heat transfer coefficients.

In this paper the simulation conditions are set as P = 8.0–9.0 MPa and CO_2 mass flux G = 150–350 kg/m^2 s. The impacts of mass flux and pressure in helically coiled tube on the heat transfer coefficient are studied and they are compared with that in the straight tube. The influence of the buoyancy force in the helically coiled tube is discussed. The correlations are proposed based on the existing simulation data under the corresponding working condition. The influences of different pressure, different mass flux on the pressure drop in the helically coiled horizontal tubes are performed after the accurate verification of the numerical simulation and they are also compared with that in the horizontal straight tubes.

2. Numerical simulation

2.1. Mathematical model

In this paper, the mathematical equations include continuity equation, momentum equation, and energy equation.

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$