J. of Supercritical Fluids 99 (2015) 112–120

Contents lists available at ScienceDirect

The Journal of Supercritical Fluids

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

Numerical investigation on heat transfer of supercritical CO_2 in heated helically coiled tubes

Kaizheng Wang [a], Xiaoxiao Xu [a,*], Yangyang Wu [a], Chao Liu [a], Chaobin Dang [b]

[a] Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Chongqing University, No. 174 Shazhengjie, Shapingba, Chongqing 400044, PR China

[b] Department of Human and Engineered Environmental Studies, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8563, Japan

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 1 February 2015
Accepted 3 February 2015
Available online 11 February 2015

Keywords:
Numerical simulation
Helically coiled tube
Supercritical CO_2
Heat transfer

ABSTRACT

Numerical simulation on heat transfer of supercritical CO_2 in heated helically coiled tubes is performed to evaluate the performance of turbulence models in predicting heat transfer of supercritical CO_2 in the helically coiled tube, and to help better understanding the heat transfer mechanism. All turbulence models yield similar tendencies in heat transfer coefficient in the helically coiled tube. The SST (shear-stress transport) model gives the best prediction to the experimental data due to accurate predictions of flow separation under adverse pressure gradients. The parameter of $Gr/Re^{2.7}$ is incapable of predicting the buoyancy effect onset of supercritical CO_2 in the helically coiled tube. The turbulent Prandtl number has little influence on the calculated heat transfer coefficient.

1. Introduction

The heat transfer of supercritical CO_2 in helically coiled tubes appears in power plant technology and cooling systems for heat pump and air-conditioning systems. Supercritical CO_2 is used as an experimental fluid to investigate mechanics of supercritical fluids. Supercritical CO_2 is use as an experimental fluid for two reasons: first, the properties of fluids have similar trends at supercritical pressures. Second, CO_2 reaches the critical point at much lower temperature and pressure compared to that of water, which results in the lower cost of performing experiments [1]. The study of heat transfer of supercritical CO_2 in helically coiled tubes is of great importance in heat exchangers design.

Experimental and numerical studies on the flow and heat transfer of supercritical fluids were performed in straight tubes [2–5]. Dang et al. [6,7] experimentally analyzed the effects of lubricating oil on heat transfer of supercritical CO_2 in horizontal tubes. An experimental investigation on heat transfer of supercritical CO_2 under cooling condition is conducted by Bruch et al. [3]. Jiang et al. [8] carried out experiments on flow and heat transfer of supercritical CO_2 in a porous tube. Experiments on heat transfer of supercritical fluids in micro-tubes were conducted by Withag et al. [9], Oh et al. [10], and Lee et al. [11].

Due to a relatively small tube-diameter used in practice and a relatively high operating pressure for supercritical CO_2, it is hard to measure the practical flow pattern of supercritical fluids directly. Numerical calculation may be the only feasible way to provide such data. Numerical simulation can potentially play a very important role in improving the understanding of the flow and heat transfer mechanism.

Jiang et al. [12] investigated the heat transfer of supercritical CO_2 in a vertical small tube. The numerical simulation was carried out by using several turbulence models. They found that the low Reynolds number turbulence model proposed by Yang–Shih [13] reproduced the general characteristic occurred in the experiments. Lots of low Reynolds number turbulence models were employed by He et al. [14] to simulate heat transfer of supercritical CO_2 flowing upwards in a vertical tube. They concluded that all of models were able to reproduce some general characteristic to some extent. V2F eddy viscosity turbulence model was used in the numerical computation of heat transfer of supercritical CO_2 in inclined pipes [15]. Research was conducted on the heat transfer of supercritical CO_2 in a vertical small tube with inner diameter of 99.2 μm and the AKN low Reynolds number turbulence model gave the better prediction of the heat transfer than the $k-\varepsilon$ realizable turbulence model [16].

Several modes were applied to simulate the heat transfer behavior in straight tubes for supercritical CO_2 and the study showed the JL model [17] gave the best prediction to the heat transfer than other models [18] based on their experimental results [19]. They also concluded that turbulent Prandtl did not have a significant

* Corresponding author. Tel.: +86 023 65112469; fax: +86 023 65112469.
E-mail address: xuxiaoxiao@cqu.edu.cn (X. Xu).

http://dx.doi.org/10.1016/j.supflu.2015.02.001
0896-8446/

Nomenclature

a	inner pipe radius [m]
A	surface area [m^2]
b	coil pitch divided by 2π [m]
c_p	specific heat at constant pressure [J/(kg K)]
C_u, C_ε, C_k	turbulence models' constants
d	tube diameter [m]
D	additional term in the k-equation
E	flow energy [W/kg]
f_1, f_2	functions in the dissipation equation
f_μ	damping function
g	acceleration due to gravity [m/s^2]
G	mass flux [kg/(m^2 s)]
Gr	Grashof number
h	heat transfer coefficient [W/(m^2 K)]
k	turbulence kinetic energy [m^2/s^2]
p	pressure [Pa]
P_k	turbulent shear production [W/m^3]
Pr	Prandtl number
q	heat flux [W/m^2]
R	curvature radius [m]
Re	Reynolds number
T	temperature [K]
u	velocity [m/s]
x	Cartesian coordinates [m]
y	normal distance from the inner wall [m]
y^+, y^*	non-dimensional distance from wall
Greek symbols	
β	volume expansion coefficient [K^{-1}]
γ	torsion [b/R]
δ	curvature ratio [a/R]
ε	rate of dissipation of k [m^2/s^3]
θ	global azimuthal angle around the curvature axis [°]
λ	thermal conductivity [W/(m K)]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
σ_k, σ_ε	turbulent Prandtl number for k and ε
τ	shear stress [N/m^2]
φ	local polar coordinates in the cross-section [°]
Subscripts	
b	bulk fluid
c	circumference of cross-section
cw	node on wall
i	general spatial indices
pc	pseudo-critical
t	turbulent quantity
w	wall

influence on the heat transfer. Cao et al. [20] numerically investigated the laminar heat transfer of supercritical CO_2 in horizontal triangle and circular tubes. The effects of fluid physical properties and buoyancy were analyzed. The heat transfer of supercritical CO_2 in the tubes was enhanced due to the effect of buoyancy. Numerical studies on heat transfer of supercritical CO_2 were performed by He et al. [21]. They adopted low Reynolds turbulence number of $k-\varepsilon$ model and V2F types. The effect of buoyancy on heat transfer and turbulence production in supercritical fluids could be very significant.

All the above mentioned studies focused on the heat transfer of supercritical fluids in straight tubes. Few studies can be found in open literature on the heat transfer of supercritical fluids in helically coiled tubes. A large amount of experimental and numerical studies of the flow and heat transfer characteristics in the helically coiled tube was concentrated in constant-property fluids, with consideration a variety of situations, such as effects of coiled parameters [22,23], phase change flow [24,25], Nanofluids flow [26,27], ice slurries flow [28], Reynolds number effects [29], Dean number effects [22,23], and so forth. Jayakumar et al. [23] numerically investigated the local Nusselt number along the length and circumference. Numerical investigation on the heat transfer of water in the helically coiled tube was conducted by Di Liberto et al. [30]. The symmetries of the heat transfer and turbulence were founded. The maximum values were located in the outer side.

Apparently, from the above mentioned researches that focus either on the heat transfer in straight pipes using supercritical fluids, or on the heat transfer in the helically coiled tubes using constant-property fluids. So, it is greatly significant to study the flow and heat transfer characteristics of supercritical CO_2 in the helically coiled tube.

In this study, the heat transfer of supercritical CO_2 is calculated by some turbulence models. The calculated results are compared with experimental results. The main contents and contributions include the following aspects. First, the performance of turbulence models in predicting the heat transfer coefficient of supercritical CO_2 in helically coiled tubes is evaluated. Second, in order to understand the heat transfer mechanism, we provide the information of the velocity and turbulence kinetic energy. Furthermore, we investigate the effect of the turbulent Prandtl number on the heat transfer of supercritical CO_2 in the helically coiled tube. The paper provides the mechanism of the heat transfer in the helically coiled tube for the design of high-efficiency heat exchanger.

2. Numerical modeling

2.1. Calculation model and turbulence model

Governing equations for the flow
Continuity:

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

Momentum:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \rho g_i - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\frac{\partial u_i}{\partial x_j}\right] \tag{2}$$

Energy:

$$\frac{\partial}{\partial x_i}(u_i(\rho E + p)) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i} + u_i \tau_{ij}\right) \tag{3}$$

where μ_t is turbulent viscosity which is based on the turbulence model.

The simulation use a number of turbulence models: standard $k-\varepsilon$ model and RNG $k-\varepsilon$ model with enhanced wall treatment, SST $k-\omega$ model [31], AB model [32], LB model [33], LS model [17], YS model [13], AKN model [34] and CHC model [35].

The transport equations for the various models can be expressed in a generic form.

$$\frac{\partial}{\partial x_i}\left[\rho k u_i - \left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] = P_k + G_k - \rho\varepsilon + \rho D \tag{4}$$

$$\frac{\partial}{\partial x_i}\left[\rho \varepsilon u_i - \left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] = (C_{\varepsilon 1} f_1 P_k + C_{\varepsilon 1} C_{\varepsilon 3} G_k - C_{\varepsilon 2} f_2 \rho\varepsilon)\frac{\varepsilon}{k} + \rho E \tag{5}$$