International Communications in Heat and Mass Transfer 91 (2018) 84–89

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Fluid flow and thermal characteristics in inclined tubes with transcritical carbon dioxide as working fluid

Wei-Mon Yan[a,*], Yen-Joe Ye[a], Alibakhsh Kasaeian[b,*]

[a] Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan
[b] Department of Renewable Energies, Faculty of New Sciences & Technologies, University of Tehran, Tehran, Iran

ARTICLE INFO

Keywords:
Inclined tubes
Transcritical fluid
Carbon dioxide
Thermal and flow characteristics

ABSTRACT

In this research work, the fluid flow and thermal characteristics in inclined tubes with transcritical carbon dioxide as working fluid were examined numerically in details. To investigate the drastic thermophysical variations of CO_2 near the critical point, the predictions with temperature-dependent thermophysical properties were presented. It was done in inclined tubes with CO_2 pressure being 8.0 MPa, the inlet temperature (T_o) 300 K and the wall temperature (T_w) 330 K with various inclined tube angles ranging from 90° (vertical upward flow) to $-90°$ (vertical downward flow). The velocity and temperature distributions, secondary flow, and friction factor coefficient were presented in detail. Predicted results showed that the effects of temperature-dependent thermophysical properties on the thermal and fluid flow characteristics in inclined tubes with transcritical carbon dioxide as working fluid are significant. Near the entrance, the C_fRe_o behaves significant changes. For the vertical upward flow, the fluid near tube wall is lighter thus the buoyancy force is upward, decreasing the downward flow velocity in the core region but increasing the fluid velocity and its gradient near the wall. For the vertical downward flow, the downward buoyancy force accelerates the fluid velocities in the core region but decreases the fluid velocities near the wall, yielding the smallest C_fRe_o among various negative inclination angles.

1. Introduction

With the growing awareness of the dual threats of ozone depletion and global warming, significant research activity has been directed to the identification and development of environmentally benign refrigerants. Carbon dioxide (R-744) is considered as a major alternative refrigerant of this century for automotive air-conditioners and heat pump systems due to its prominent thermodynamic, transport, and environmentally benign properties [1]. The viscosity of CO_2 becomes very low while its specific heat becomes very large near the critical point. The thermophysical properties of carbon dioxide are so outstanding, that it is used in a number of technical applications. In spite of having a high pressure, CO_2 may be a good choice if the engineers need better performing and cost-effective heat exchangers.

Pitla et al. [2] presented a review of the heat transfer and pressure drop characteristics of supercritical carbon dioxide in tube flow. This information was necessary for designing the gas cooler of a carbon dioxide refrigeration system. A comparison of the different heat transfer correlations applicable to cooling of supercritical carbon dioxide were also proposed. The heat transfer characteristics of supercritical carbon dioxide in different flow directions under heating conditions were examined experimentally by Liao and Zhao [3]. They indicated that the heat transfer was enhanced for both upward and horizontal flows, but was deteriorated around pseudo-critical point for downward flow. The forced convection heat transfer for carbon dioxide flowing inside a heated tube at supercritical conditions was investigated by Scalabrin and Piazza [4] using neural networks. They indicated that an improved performance of the neural networks was found with respect to conventional correlations.

Yoon et al. [5] presented the experimental data for the heat transfer and pressure drop characteristics obtained during the gas cooling process of carbon dioxide in a horizontal tube. The experimental results were compared with the existing correlations for the supercritical heat transfer coefficient, which generally under-predict the measured data. Dang and Hihara [6,7] experimentally and numerically examined the heat transfer of supercritical CO_2 in horizontal tubes. Effects of inner diameter, mass flux, heat flux and pressure on heat transfer coefficient were studied in details, assuming that the flow was axisymmetric and the buoyancy effect was neglected. Huai et al. [8] presented the fluid flow and heat transfer characteristics of supercritical CO_2 in a

* Corresponding authors.
E-mail addresses: wmyan@ntut.edu.tw (W.-M. Yan), akasa@ut.ac.ir (A. Kasaeian).

https://doi.org/10.1016/j.icheatmasstransfer.2017.12.004

Nomenclature

C_f	finning fraction factor
c_p	specific heat (J kg^{-1} K^{-1})
d	tube diameter (m)
g	gravity acceleration (ms^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
L	Tube length (m)
p	pressure (Pa)
r	radial coordinate (m)
R	tube diameter (m)
Re	Reynolds number
T	temperature (K)
U	dimensionless velocity in the x-direction, u/u_o
u, v, w	velocity component the x-, y-, and z- directions (m s^{-1})
X	dimensionless axial location, $x/(d)$
x, y, z	coordinates (m)

Greek symbols

δ	Inclined angle
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
φ	circumferential angle of tube

Subscripts

c	critical point
o	Inlet
w	wall

horizontal multi-port extruded aluminum test section consisting of 10 circular channels with an inner diameter of 1.31 mm. The results showed that the operating pressure, the mass velocity and the temperature of CO_2 had considerable impact on fluid flow and heat transfer characteristics. The heat transfer coefficient and pressure drop during gas cooling process of CO_2 (R744) in a horizontal tube were investigated experimentally by Son and Park [9]. Measured results indicated that the local heat transfer coefficient of CO_2 agrees well with the correlation by Bringer-Smith. However, at the region near pseudocritical temperature, the experiments revealed higher values than the Bringer-Smith correlation. Based on the experimental data, a new correlation to predict the heat transfer coefficient of supercritical CO_2 during in-tube cooling was developed.

Jiang et al. [1,10] experimentally investigated the convective heat transfer of supercritical pressure CO_2 in vertical mini tubes. They indicated that the heat transfer coefficient increases firstly and then decreases as heat flux increases when inlet Reynolds number exceeding 4000. The heat transfer was greatly enhanced for downward flow with higher heat flux at low Reynolds number. The heat transfer deterioration occurred for both upward and downward flows mainly owing to the flow acceleration when the inlet Reynolds number is < 2900. Bruch et al. [11] experimentally studied the heat transfer characteristics of supercritical CO_2 in vertical tubes. The measured results showed that the heat transfer coefficient increased as the mass flux increased for upward flow, but different results were found for downward flow. Jiang et al. [12] examined experimentally the convection heat transfer of carbon dioxide at supercritical pressures in a vertical tube for various Reynolds numbers, heat fluxes and flow directions. The results showed that the effects of flow acceleration are significant and the local wall temperature varied non-linearly for both upward and downward flows at the pressures in the vicinity of critical point and low inlet Reynolds numbers when the heat fluxes are relatively high. The buoyancy effect on the heat transfer was negligible in micron scale tubes at inlet Reynolds and various heat fluxes.

Laminar mixed convective flow and heat transfer in a 0.5 mm diameter and 1000.0 mm length tube was examined numerically by Yang et al. [13]. The supercritical carbon dioxide in the tube was cooled at constant wall temperature. Predicted results showed that under the mixed convective flow and heat transfer conditions, the horizontal flow display the largest heat transfer coefficients. The inclined flows at 30° and − 30° also performed better heat transfer qualities among various inclination angles. Recently, Ma et al. [14] constructed a supercritical CO_2-water test loop to study the heat transfer performance of supercritical CO_2 in a double pipe heat exchanger. The effects of supercritical CO_2-side pressure, mass flux and buoyancy force as well as water-side mass flux were investigated. Measured data showed that the total and supercritical CO_2-side heat transfer coefficients reduced as the supercritical CO_2-side pressure increased. The peak total and supercritical CO_2-side heat transfer coefficients appeared at a higher temperature than the pseudo critical temperature.

As mentioned above, most of the existing literatures have focused on the convective heat transfer characteristics and the buoyancy effect of supercritical CO_2 in vertical or horizontal tubes under cooling conditions. Actually, the fluid flow and thermal characteristics of supercritical CO_2 in inclined tubes under heating conditions have great significance for the design of heat exchangers. This research study was critically focused on these significant aspects.

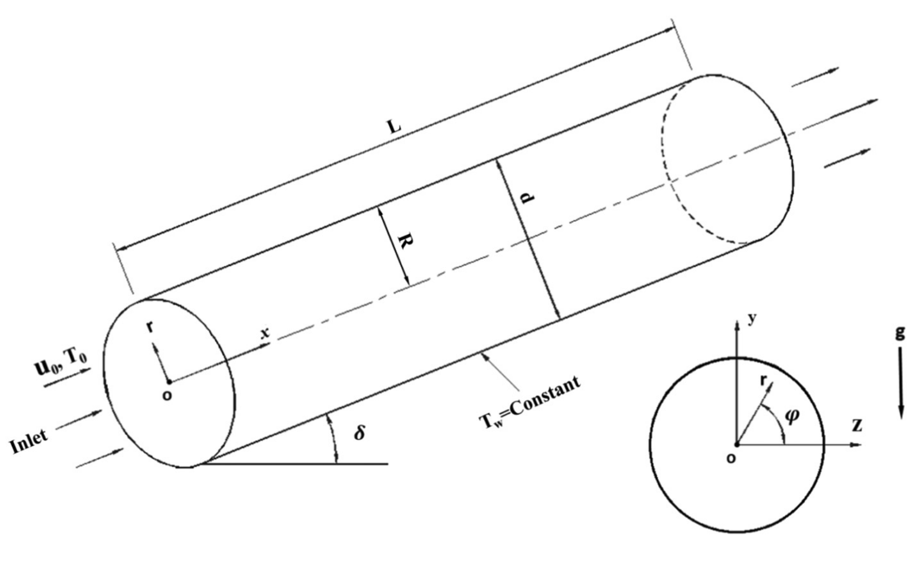

Fig. 1. Schematic representation of the prediction system.