International Communications in Heat and Mass Transfer 41 (2013) 68–75

Contents lists available at SciVerse ScienceDirect

International Communications in Heat and Mass Transfer

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

Turbulent heat transfer of Al_2O_3–water nanofluid inside helically corrugated tubes: Numerical study ☆

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ARTICLE INFO

Available online 8 December 2012

Keywords:
Turbulent heat transfer
Helically corrugated tube
Nanofluid
Mixture model

ABSTRACT

Turbulent heat transfer in heated helically corrugated tube was investigated numerically for pure water and water–alumina nanofluid using two phase approach. The study was carried out for different corrugating pitch and height ratios at various Reynolds numbers ranging from 10,000 to 40,000. The effect of nano-particles in heat transfer augmentation for smooth tube and helically corrugation tubes (HCT) was discussed and their relative Nusselt number was compared. Results show that the heat transfer enhancement is promoted extremely by increasing the volume fraction of nano-particles. Adding 2% and 4% nano-particles by volume to water enhances the heat transfer by 21% and 58%, respectively. Also, the overall enhancement in heat transfer using two mechanisms simultaneously compared to using pure fluid within smooth tube exceeds over 330%. A correlation is given based on curve fitting from numerical data. Results indicate that using nano-particles yields different enhancement in heat transfer of tube for different corrugation height and pitch.

1. Introduction

Heat transfer enhancing techniques are used in heat exchanger to reduce and promote the size and performance, respectively. Generally, there are two group techniques for augmenting the heat transfer: passive and active techniques. One of the best passive techniques is based on introducing surface roughness that disturbs the boundary layer and promoting the turbulence near surfaces. Several roughened tube such as finned tubes, helical tubes, fluted tubes and elliptical axis tubes were investigated by many researchers [1–5]. Among them, the helically corrugated geometries are most considered. Helical corrugation creates the chaotic flow mixing and reducing the thickness of thermal boundary layer that increases the heat transfer. They are capable to increase the heat transfer rate up to 400%. There are extensive experimental studies carried out to consider the effect of corrugation shape on heat transfer for various fluids over the last three decades. The effect of different corrugation pitch on thermal performance and convective heat transfer was studied by Rainieri and Pagliarini [6]. They found that helical corrugation induces swirl component that intensifies the heat transfer. Barba et al. [7] studied experimentally the heat transfer enhancement and pressure drop in a corrugated tube for ethylene glycol at Reynolds number ranging from 100 to 800. They presented a correlation for Nusselt number based on fitting results. An experimental study was performed by Dong et al. [8] for water and oil in two tubes heat exchanger. They used the four spirally corrugated tubes as inner tube with different geometry. They found that enhanced tube can increase the tube side heat transfer coefficient and friction factor up to 120% and 160%, respectively. Also their result shows that enhancing the heat exchanger performance is depending to Reynolds number, Prandtl number and geometry of corrugation. Vicente et al. [9,10] performed several experiments for laminar, transient and turbulent flows in the HCT with different corrugation height and pitch. They measured the isothermal friction factor and Nusselt number. Results show that heat transfer does not sensitively change in laminar flow while it intensifies in the turbulent flow. They represented this phenomenon that helical corrugation as roughened surfaces increases flow turbulence and mixes in the near-wall flow, which is effective in turbulent flow but not in laminar flow. Naphon et al. [11] conducted experimental study on the heat transfer and friction factor in horizontal double pipes using helical ribbed tube. They investigated the effect of relative height and pitch of corrugation on the heat transfer and pressure drop. They used helical ribbed tube with diameter lesser than 10 mm against other researchers. In agreement with others, they found that the height of corrugation has more significant effect in respect to corrugation pitch on heat transfer and pressure drop. Laohalertdecha and Wongwises [12] studied the effect of corrugation pitch on the condensation heat transfer coefficient and pressure drop of R-134a inside a horizontal HCT. Result indicates that the corrugation pitch has significant effect on heat transfer which increases by increasing the pitch to diameter ratio. Petkhool et al. [13] investigated the turbulent heat transfer

☆ Communicated by Dr. W.J. Minkowycz
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http://dx.doi.org/10.1016/j.icheatmasstransfer.2012.11.006

Nomenclature

C_p	specific heat, J/kg
d	tube diameter, m
d_f	molecular diameter of base fluid, m
d_p	nanoparticle diameter, m
E	Energy, J/kg
e	Corrugation height, m
K	thermal conductivity (W/m K)
k	turbulent kinetic energy, m^2/s^2
Nu	Mean Nusselt number, hd/K_{eff}
P	pressure (pa)
p	Corrugation pitch, m
Pr	Prandtl number, ν_{eff}/α_{eff}
q''	heat flux, w/m^2
Re	Reynolds number, $V_m d/\nu_{eff}$
T	Temperature, K
V	Velocity, m/s
Z	axial direction

Greece symbols

ρ	Density, kg/m^3
β	volumetric expansion coefficient,1/K
α	thermal diffusivity, m^2/s
ϕ	volume fraction
ν	kinematics viscosity, m^2/s
μ	dynamic viscosity, kg.m/s
ε	Dissipation of turbulent kinetic energy, m^2/s^3

Subscripts

b	bulk
dr	drift
eff	effective
f	base fluid
k	summation index
nf	Nano-fluid
m	mixture
s,f	smooth tube and pure fluid

enhancement in a concentric tube heat exchanger with helically corrugated tube as inner tube. They studied the effect of three different piths to diameter ratio and three different heights to diameter ratio on heat transfer and isothermal friction augmentation. They proposed a correlation based on their results for Reynolds number ranging from 5500 to 60,000. Alternative heat transfer enhancing method is related to adding the nano-particles to based fluid that increases the heat transfer through enhancing the thermal conductivity of nanofluid. This method is vastly studied experimentally and numerically by many researchers in various geometries, especially in the heat exchanger because of its extensive application in engineering industries. In general, there are two methods for simulation of nanofluid: single phase and two phase model. In the single phase model it is assumed that the nano-particles and fluid phase are in hydrodynamics and thermal equilibrium while two phase model has high accuracy in real especially in the complicated flow and fluid with bigger nano-particles. Allahyari et al. [14] solved the laminar flow inside the non-uniform heating tube by two phase approach. Bianco et al. [15] applied this method in investigating the heat transfer inside horizontal tube with constant wall temperature. They performed a comparison between two and single phase models to find that the two phase model is more precise than single phase model. Following them, Mokhtari Moghari et al. [16] studied numerically the laminar mixed convection heat transfer in an annulus using two phase approach. They used Al_2o_3–water as nanofluid. Their result shows that increasing nano-particle volume fraction increases the Nusselt number while it does not have significant effect on friction factor. Recently, many researchers focused on using the two heat transfer enhancing techniques simultaneously, for example using coil insert and twist tape with nano-particles in circular tube [17,18]. Wongcharee and Eiamsa-ard [19] investigated experimentally the enhancement of heat transfer using CuO/water nanofluid and twisted tape with alternate axis. They performed experiments for laminar regime in Reynolds number ranging from 830 to 1990 and concentration of nano-particle ranging from 0.3% to 0.7% by volume. Results indicate that employing the 0.7% volume fraction of nano-particle and twist tape simultaneously promotes the thermal performance by factor of 5.53 for Reynolds number of 1990. Suresh et al. [20] conducted an experimental study on heat transfer and isothermal friction characteristics of CuO/water nanofluid with low concentration in dimpled tube. They performed a comparison of heat transfer between plain tube/water and dimpled tube/nanofluid indicating enhancing up to 27% for the second case. Wongcharee and Eiamsa-ard [21] carried out an experimental study of turbulent heat transfer by using CuO/water nanofluid inside corrugated tube equipped with twist tape. They compared the heat transfer and friction factor of nanofluid inside roughened tube with pure fluid inside plain tube. Result showed the maximum thermal performance factor 1.57 was achieved with the use of CuO/water nanofluid at concentration of 0.7% by volume in corrugated tube together with twisted tape at twist ratio of 2.7.

Rabienataj Darzi et al. [22] conducted an experimental study of heat transfer and friction factor of SiO_2–water nanofluid inside five different helically corrugated tubes. They compared the Nusselt number, friction factor and thermal performance of heat exchanger between plain tube and corrugated tubes with and without nano-particles. Results indicated roughened tubes with higher height and smaller pitch of corrugation intensifies the enhancement of heat transfer induced by nano-particles.

Despite the great amount of experimental work on corrugated tubes, it can be stated that the flow nature is still unknown due to complication of flow in the helically corrugated tubes. Numerical simulation can be conducted to better find the heat transfer and flow field characteristics. Based on the best knowledge of authors, there is not any numerical solution of turbulent flow in these tubes. The present study investigated the heat transfer of nano-fluids within HCT numerically. For this purpose two phase approach model was applied and flow characteristics were obtained in detail within HCT. It should be considered that these tubes can be more useful for fluid consisted of solid particle due to self-cleaning and existence of chaotic flow mixing. It means that these tubes can be more efficient for nano-fluids and therefore, its study can be interesting.

2. Physical model and mathematical modeling

Fig. 1 shows that the considered configuration consists of the HCT with a length of 2.036 m and a diameter (d) of 0.018 m. The corrugation pitch (p) and height (e) considered based on Vicente's work [10] are given in Table 1. The physical properties of the fluid are assumed to be constant. Al_2o_3 with a mean diameter (d_p) of 28 nm is considered as nano-particles. Thermo-physical properties of water and nano-particles are given in Table 2. Dissipation and pressure work are neglected. Thus, with these assumptions the conservation equations for steady state mixture model are as follows:

Continuity equation:

$$\nabla.\left(\rho_{eff}V_m\right) = 0 \tag{1}$$