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Experimental investigation of turbulent heat transfer and flow characteristics of SiO_2/water nanofluid within helically corrugated tubes ☆

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ABSTRACT

Experiments were conducted to investigate the effect of nanofluid on turbulent heat transfer and pressure drop inside concentric tubes. Water and SiO_2 with mean diameter of 30 nm were chosen as base fluid and nano-particles, respectively. Experiments were performed for plain tube and five roughened tube with various heights and pitches of corrugations. Results show that adding the nano-particles in tube with high height and small pitch of corrugations augments the heat transfer significantly with negligible pressure drop penalty. It is discussed on relative Nusselt number and thermal performance of heat exchanger.

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 [1–8]. Among them, the helically corrugated geometries have been most considered. Helically corrugation creates the chaotic flow mixing and reducing the thickness of thermal boundary layer that increases the heat transfer.

Vicente et al. [9,10] performed several experiments for laminar, transient and turbulent flows in the HCT with different corrugation heights and pitches. 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 increase 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 corrugations on the heat transfer and pressure drop. They used helical ribbed tube with diameter lesser than 10 mm against of 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 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 base on their results for Reynolds number ranging from 5500 to 60,000. Another passive method as alternative heat transfer enhancing method is related to adding the nano-particles to based fluid. It increases the heat transfer through with 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.

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 [14,15]. Wongcharee and Eiamsa-ard [16] 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 by 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. [17] conducted an experimental study on heat

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Nomenclature

A	Tube area, m^2
C_p	Specific heat, J/kg
D	Tube diameter, m
E	Corrugation height, m
F	Friction factor
H	heat transfer coefficient, W/m^2K
K	Thermal conductivity, W/mK
L	Tube length, m
$\dot{m}$	Mass flow rate, kg/s
Nu	Nusselt number
P	Corrugation pitch, m
P	Pressure, Pa
Pr	Prandtl number
Re	Reynolds number
T	Temperature, K
U	Velocity, m/s

Greece symbols

ρ	Density, kg/m^3
μ	Viscosity, kg m/s
φ	concentration of nano-particles

Subscripts

ave	average
b	bulk
c	cold
h	hot
f	fluid
i	inner
in	inlet
nf	nanofluid
out	outlet
p	Nano-particles
w	Tube wall

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 [18] investigated the effect of CuO nano-particles on heat transfer from corrugated tube equipped with twist tape.

Present experiment deals with the enhancement of the heat transfer thorough with helically corrugation and adding the nano-particles to the base fluid. The effect of different volume concentrations of nano-particles on heat transfer from HCT with various heights and pitches of corrugation are discussed in following section.

2. Experimental apparatus and procedure

2.1. Experimental apparatus

The schematics diagram of the experimental apparatus is shown in Fig. 1. the test loop consist of cold and hot water pump, hot water tank, nanofluid tank as cold fluid tank, cooling unit and concentric tubes as test section. The length of test section was 220 cm copper tube with inner diameter of 8.1 mm and steel tube with a diameter of 150 mm was selected as inner and outer tubes of test section. The outer surface of test section was isolated thermally from surrounding with thick layer of glass wool. To minimize the heat loss resulting from axial heat conduction, the test section was isolated thermally from its upstream and downstream sections by plastic bushings. The temperature of inlet and outlet of tubes was measured by K-type thermocouples and the wall temperature of inner tube was measured by 6 K-type thermocouples attached by special epoxy to the surface of inner tube. Omega data logger (OM-SQ2020) was used to record the temperatures. The uncertainty in temperature measurement was ±0.1 °C. The pressure drop along test section was measured by Rosemount 3051 pressure transmitter with reference accuracy of ±0.04%. Corrugated tubes were fabricated from the copper tube with an inner diameter of 8.1 mm and outer diameter of 9.57 mm before the rolling operation. Corrugated tubes were manufactured by cold rolling the outer surfaces of plain tube. Fig. 2 shows some of the manufactured tubes with different heights and pitches of corrugation. The geometry of these tubes is given in Table 1. SiO_2 nano-particles with a mean diameter of 30 nm were purchased from Degussa Co. (Germany). Distilled water was added to a specified amount of nanoparticles and mixed together by magnetic stirrer for half an hour. After that, it was dispersed by ultrasonic vibrator for 2 h to get the stable suspension. It should be mentioned that due to changing the thermo-physical properties of nanofluid, no surfactant/dispersant additives were added during the synthesis process. Fig. 3 shows the samples of prepared nanofluids with different concentrations.

2.2. Data reduction

The average Nusselt number and friction factor basis of inner diameter of tube can be expressed as below:

$$Nu = \frac{hd_i}{k} \tag{1}$$

$$f = \frac{\Delta P}{\frac{1}{2}\rho u^2 \left(\frac{L}{d_i}\right)}. \tag{2}$$

where ρ is density of working fluid, k is thermal conductivity of fluid, ΔP is pressure drop along inner tube, L is test section long and h is convective heat transfer coefficient which is defined as:

$$h = \frac{Q_{ave}}{A_i(T_w - T_b)}. \tag{3}$$

where T_w is the average wall temperature that estimates from the attached thermocouples over inner tube and T_b is average (bulk) temperature of fluid. The average heat flux is calculated as:

$$Q_{ave} = \frac{1}{2}(Q_c + Q_h). \tag{4}$$

Q_c is the heat transferred to cold fluid in inner tube which is calculated as:

$$Q_c = \dot{m}_c C_{pc}\left(T_{c,out} - T_{c,in}\right). \tag{5}$$

where $\dot{m}_c$ is the mass flow rate of cold fluid; C_{pc} is the specific heat of cold fluid; $T_{c,in}$ and $T_{c,out}$ are the inlet and outlet cold fluid temperatures, respectively. Q_h is the heat transferred from hot fluid in outer tube that is expressed as:

$$Q_h = \dot{m}_h C_{ph}\left(T_{h,in} - T_{h,out}\right). \tag{6}$$

where $\dot{m}_h$ is the hot water mass flow rate; $T_{h,in}$ and $T_{h,out}$ are the inlet and outlet hot fluid temperatures, respectively. The thermal and physical properties of nanofluids such as density, viscosity, specific heat and