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Numerical study on turbulent heat transfer and pressure drop of nanofluid in coiled tube-in-tube heat exchangers

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ABSTRACT

A computational fluid dynamics (CFD) study has been carried out to study the heat transfer and pressure drop characteristics of water-based Al_2O_3 nanofluid flowing inside coiled tube-in-tube heat exchangers. The 3D realizable k–ε turbulent model with enhanced wall treatment was used. Temperature dependent thermophysical properties of nanofluid and water were used and heat exchangers were analyzed considering conjugate heat transfer from hot fluid in the inner-coiled tube to cold fluid in the annulus region. The overall performance of the tested heat exchangers was assessed based on the thermo-hydrodynamic performance index. Design parameters were in the range of; nanoparticles volume concentrations 0.5%, 1.0% and 2.0%, coil diameters 0.18, 0.24 and 0.30 m, inner tube and annulus sides flow rates from 2 to 5 LPM and 10 to 25 LPM, respectively. Nanofluid flows inside inner tube side or annular side. The results obtained showed a different behavior depending on the parameter selected for the comparison with the base fluid. Moreover, when compared at the same *Re* or *Dn*, the heat transfer coefficient increases by increasing the coil diameter and nanoparticles volume concentration. Also, the friction factor increases with the increase in curvature ratio and pressure drop penalty is negligible with increasing the nanoparticles volume concentration. Conventional correlations for predicting average heat transfer and friction factor in turbulent flow regime such as Gnielinski correlation and Mishra and Gupta correlation, respectively, for helical tubes are also valid for the tested nanofluids which suggests that nanofluids behave like a homogeneous fluid.

1. Introduction

Heat exchangers performance can be improved by heat transfer enhancement techniques. There are three broad classifications of heat transfer enhancement techniques: Passive techniques which do not require any external power such as treated surfaces, rough surfaces, extended surfaces, swirl flow devices, displaced enhancement devices, coiled tube, surface tension device, and additives such as nanoparticles: Active techniques which require external power to facilitate the desired flow modification for augmenting heat transfer such as mechanical aids, surface vibration, fluid vibration, electrostatic fields, injection, suction, and jet impingement: Compound technique is the combination of any two or more of the above mentioned techniques simultaneously [1].

Coiled tube-in-tube heat exchangers (CTITHEs) belong to the most common passive heat transfer enhancement devices in many applications including HVAC applications, cryogenic process, chemical and food industries, waste heat recovery, and space applications. They provide a large surface area per unit volume. Enhancement in heat transfer due to helical coils has been reported by many researchers. Thus, several studies have investigated the flow and heat transfer characteristics for single-tube and double-tube helical heat exchangers, both experimentally, as well as numerically. The secondary flow motion induced by the curvature effect and the resultant centrifugal force make heat transfer coefficient greater than that in a straight pipe. Also, torsion of helically coiled tubes causes more complication in temperature and velocity fields. Concerning flow and heat transfer in helical tubes, it is suggested to refer to the most recent review papers of Vashisth et al. [2] and Naphon and Wongwises [3] and the references cited therein.

On the other hand, the inherently low thermal conductivity of conventional heat transfer fluids such as water, ethylene glycol or engine oil greatly limits the heat transfer performance of heat exchangers. In comparison with metallic or nonmetallic materials such as Al_2O_3, CuO, Cu, TiO it is found that the thermal conductivity of conventional heat transfer fluids are typically order-of-magnitude lower. Recent works have shown that the presence of

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Nomenclature

a	diameters ratio, $d_{i,o}/d_{o,i}$
C_2	model constant
C_p	Specific heat at constant pressure, J/kg K
C_μ	model parameter
D	coil diameter, m
Dn	Dean number, $Re\ \delta^{0.5}$
d	tube diameter, m
f	Darcy–Weisbach friction factor
h	Heat transfer coefficient
H	coil pitch, m
I	turbulence intensity
k	turbulent kinetic energy, m^2/s^2
K	thermal conductivity, W/m K
L	length of the tube, m
Nu	Nusselt number, hd_h/K
p	pressure, Pa
Pr	Prandtl number, $C_p\mu/K$
q	heat flux, W/m^2
Qc	cold water flow rate, LPM
Qh	hot water flow rate, LPM
R	coil radius, m
Re	Reynolds number, $\rho u d_h/\mu$
T	temperature, K
u	velocity component in flow direction, m/s
u'	Root-mean-square turbulent velocity fluctuation, m/s
y	distance from wall, m
y^+	dimensionless distance from wall, $u_\tau y/v$
Y_i	quality characteristics

Greek symbols

Δ	difference operator
δ	curvature ratio, $\delta = d_h/D$
δ_{ij}	Dirac delta function
ε	turbulent dissipation rate, m^2/s^3
η	thermo-hydrodynamic performance index
θ	axial angle, °
μ	dynamic viscosity, kg/m s
v	kinematic viscosity, m^2/s
ρ	density of test fluid, kg/m^3
σ_τ	turbulent Prandtl number in energy equation
σ_k	diffusion Prandtl number for k
σ_ε	diffusion Prandtl number for ε
φ	nanoparticles volume concentration

Subscripts

b	bulk quantity
bf	base fluid
c	cold
h	hot
i	inner or inlet
i,j,k	general spatial indices
l	laminar quantity
nf	nanofluid
o	outer or outlet
P	nanoparticle
S	straight tube
t	turbulent quantity
w	wall condition.

Superscripts

+	standard wall coordinates

the nanoparticles (average size below 100 nm) in the fluids at low particle loadings increased the effective thermal conductivity of the fluid and consequently enhanced the heat transfer characteristics [4]. Because of their unique features, nanofluids have attracted attention as a new generation of fluids in heat exchangers, technological plants, automotive cooling applications and many other applications [4–7].

So far, studies on turbulent convective heat transfer characteristics of nanofluids in helically coiled tubes or double-pipe helical heat exchangers are scarce. Akbarinia and Behzadmehr [8] studied laminar mixed convection of a nanofluid in curved tubes using homogeneous model. The results showed that the buoyancy force had a negative effect on the Nusselt number and concentration had positive effect on the heat transfer enhancement. Akbarinia [9] numerically investigated laminar mixed convection of water-based Al_2O_3 nanofluid, buoyancy-affected and heat transfer of a curved tube. Simultaneous effects of the buoyancy force, centrifugal force and nanoparticles concentration on the fluid flow and heat transfer along the pipe were investigated. The effect of nanoparticles diameter on a laminar nanofluid flow in a curved tube has been investigated by Akbarinia and Laur [10] at a Reynolds number of 648 and a Grashof number of 5740 using a two phase approach and control volume technique. They concluded that the increase of the diameter of nanoparticles did not change the flow behavior. Sasmito et al. [11] conducted a numerical study on laminar nanofluid flows (alumina/water and copper/water) in coiled square tubes, and stated that adding 1% nanofluid (volumetric concentration) improved the heat transfer performance; however, further addition tended to deteriorate heat transfer performance. The heat transfer characteristics of a double tube helical heat exchanger were numerically investigated under laminar flow conditions by Huminic and Huminic [12]. CuO and TiO_2 nanoparticles were dispersed in water with a volume concentration of 0.5–3%. A 14% increase in heat transfer rate was observed for 2% CuO nanoparticle concentration but the enhancement begins to worsen because higher particle concentration leads to higher viscosity. An experimental investigation has been carried out by Hashemi and Akhavan-Behabadi [13] to study the heat transfer and pressure drop characteristics of nanofluid flow inside horizontal helical tube under constant heat flux and laminar flow regime. CuO nanoparticles were dispersed in base oil with a volume concentration of 0.5–2%. Choi and Zhang [14] analyzed laminar forced convection heat transfer of Al_2O_3–water nanofluid in a pipe with a return bend by using the finite element method. The results show that the average Nusselt number increases with increasing Reynolds number and Prandtl number, and the increment of specific heat in the nanofluid contributes to heat transfer enhancement. However, the pressure drop in the pipe largely increases with the increment of nanoparticle volume concentration. Narrein and Mohammed [15] performed numerical investigation of effects of different nanoparticles types (Al_2O_3, SiO_2, CuO, ZnO), base fluid types (water, ethylene glycol, engine oil), diameters (25–80 nm) and volume concentrations of nanoparticles (0–4%) on the hydraulic and thermal characteristics in helically coiled tube heat exchangers under laminar flow conditions. Their results revealed that nanofluids can enhance the thermal properties and performance of the helically coiled tube heat exchanger but it is accompanied with a slight increase in pressure drop. Moreover, they found that the Nusselt