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Heat transfer and entropy generation analyses of nanofluids in helically coiled tube-in-tube heat exchangers☆

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ABSTRACT

In this work, a three-dimensional analysis is used to study the heat transfer and entropy generation inside a helically coiled tube-in-tube heat exchanger in laminar flow regime using two different types of nanofluids. Overall heat transfer coefficient, effectiveness, Nusselt number, and entropy generation of helically coiled tube-in-tube heat exchanger were investigated considering the nanoparticle volume concentrations between 0 and 2.0 vol.%. The mass flow rate of the nanofluid from the inner tube was kept and the mass flow rate of the water from the annulus was set at either half, full, or double the value. The present contribution is a companion paper of Huminic and Huminic [1].

The numerical results reveal that the use of nanofluids in a helically coiled tube-in-tube heat exchanger improves the heat transfer performances. Thus, the maximum effectiveness was 91% for 2% CuO nanoparticles and 80% for 2% TiO_2 nanoparticles. Also, the increase of nanoparticles volume concentration leads to the Nusselt number increase and the reduction of the entropy generation due heat transfer effects, the viscous effects to entropy generation being negligible.

1. Introduction

Helically coiled tubes are efficient heat transfer equipments due to their compact size and high heat transfer performance in comparison with straight tube heat exchangers used in various industrial applications ranging from heat exchangers, power plant, electronics, environmental engineering, manufacturing industry, air-conditioning, waste heat recovery, cryogenic processes, to chemical processing. Several studies have been conducted to analyze the heat transfer and flow characteristics of helically coil heat exchangers in laminar and turbulent flow regimes. The most prominent characteristic of flow in helically coiled tubes is the secondary flow induced by centrifugal force due to the curvature of the pipe. Consequently, the heat transfer and the friction factor in helically coiled heat exchangers are significantly larger than in straight pipes [2,3]. In the last years, the heat transfer intensification has been reported due to the use of nanofluids. The most remarkable characteristics of these fluids comprise improved heat transfer features, such as thermal conductivity and convective heat transfer coefficient in comparison to the base fluid.

To the best of the authors' knowledge, the studies concerning the thermal performances and the second law of thermodynamics inside helically coiled tube-in-tube heat exchangers are limited. The aim of the present investigation is to study the heat transfer and entropy generation of nanofluids under laminar flow condition inside both of the tube and annular sides of helically coiled tube-in-tube heat exchangers for two types of nanofluids with different nanoparticles volume concentrations and different mass flow rates. The present contribution is a companion paper of Huminic and Huminic [1].

2. Literature review

Suresh et al. [4] studied the convective heat transfer and friction factor characteristics in the plain and helically dimpled tube under turbulent flow. Constant heat flux was adopted as thermal boundary condition. Water and copper oxide nanoparticles (CuO) were used as working fluid. CuO nanoparticles of 15.3 nm size were synthesized by sol–gel method. The effects particle concentration (0.1 vol. %, 0.2 vol. %, and 0.3 vol %) and of the dimples were examined. The experiments were performed for the Reynolds number in the range 2500–6000. The results showed that the Nusselt number with dimpled tube and nanofluids was about 19%, 27%, and 39% (for 0.1%, 0.2%, and 0.3% volume concentrations, respectively) higher than the Nusselt number obtained with plain tube and water. Also, the pressure loss of the nanofluids increase slightly compared with that of distilled water. Finally, two correlations for the Nusselt number and the friction factor were proposed:

$$Nu = 0.00105 Re^{0.984} Pr^{0.4} (1+\phi)^{-80.78} \left(1+\frac{p}{d}\right)^{2.089} \quad (1)$$

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Nomenclature

A_0	Surface area of tube (m)
c_p	Specific heat at constant pressure (J/kgK)
C	Heat capacity rate
d	Tube diameter (m)
d_h	Hydraulic diameter (m)
d_p	Particle diameter (m)
Dn	Dean number
f	Friction factor
h	Heat transfer coefficient (W/m^2K)
He	Helical number
L	Coil length (m)
$LMTD$	Log-mean temperature difference (K)
k	Thermal conductivity (W/mK)
$\dot{m}$	Mass flow rate (kg/s)
Nu	Nusselt number
NTU	Number of transfer units
p	Pitch ratio
P	Pressure (Pa)
Pr	Prandtl number
r	Distance from the pipe centerline (m)
R	Radius (m)
Re	Reynolds number
q	Heat transfer per unit of length (W/m)
Q	Heat transfer rate (W)
S_{gen}	Entropy generation (W/K)
T	Temperature [K]
U_o	Overall heat transfer (W/m^2K)
U	Velocity (m/s)
x, y, z	cartesian coordinates (m)
Greek symbol	
Δp	Pressure drop (Pa)
ΔT_1	Outlet temperature difference (K)
ΔT_2	Inlet temperature difference (K)
ρ	Density (kg/m^3)
μ	Dynamic viscosity (Pas)
ε	Effectiveness
φ	Volume concentration of nanoparticles
Subcript	
an	Annulus
ave	Average
BF	Base fluid
in	Inlet
int	Inner
NF	Nanofluid
out	Outlet
max	Maximum
min	Minimum

Pakdaman et al. [5,6] investigated the thermophysical properties, the heat transfer, and the pressure drop of MWCNT/oil nanofluids flow inside vertical helically coiled tubes. Constant wall temperature was adopted as thermal boundary condition. The experiments were carried out on oil-based Walled Carbon NanoTube (MWCNT) nanofluids containing 0.1%, 0.2%, and 0.4% by weight nanoparticles at 40–70 °C. The results illustrated that suspending nanoparticles in the base fluid enhances its thermophysical properties noticeably. The presented results showed, also, that the high overall performance index of up to 6.4 was obtained for the simultaneous utilization of both heat transfer enhancement techniques (nanofluid and helical coil). Behabadi et al. [7] investigated heat transfer using Multi-Walled Carbon Nanotubes (MWCNT) dispersed in heat transfer oil flow in a vertical helical coil. The results revealed that nanofluid flows showed much higher Nusselt numbers compared to the base fluid flow.

Kannadasan et al. [8] performed a comparison of heat transfer and pressure drop characteristics in a helically coiled heat exchanger held in horizontal and vertical positions. The experiments were carried out on water-based copper oxide (CuO) nanofluids containing 0.1% and 0.2% by volume nanoparticles and the Dean number between 1600 and 4000. The results revealed that the Nusselt number for the nanofluid with of 0.2% volume concentration was 47% when compared to water in horizontal position and of 48% in vertical position, which means that no are difference between horizontal and vertical arrangements. The results showed, also, the friction factor increases while increasing particle volume concentration. Finally, two correlations for the Nusselt number and the friction factor were developed:

Hashemi and Akhavan-Behabadi [9] studied pressure drop and heat transfer characteristics inside horizontal helically coiled pipe. Constant heat flux was adopted as thermal boundary condition. Oil and copper oxide (CuO) were used as working fluid. The experiments were performed for nanofluids with the weight concentrations of 0.5%, 1%, and 2%, and the Reynold number between 10 and 100. They defined a parameter called performance index so as to find the optimum work conditions of two enhanced heat transfer techniques, nanofluid and helical pipe. The results showed that the nanofluids have better heat transfer characteristics when they flow in helical tube rather than in the straight tube. Compared to base oil flow, maximum heat transfer enhancement of 18.7% and 30.4% was obtained for nanofluid flow with 2 wt.% concentration inside the straight tube and helical tube, respectively. A new correlation for the Nusselt number was proposed:

$$Nu = 41.730 Re^{0.346} Pr^{-0.286} (1+\phi)^{0.180} \quad (2)$$

the applicable in the range $< \phi < 2.0\,\%$, $Re < 125$, $700 < Pr < 2050$.

Kahani et al. [10] performed a comparative study between metal oxide nanopowders on thermal characteristics of nanofluid flow through helical coils. Constant heat flux was adopted as thermal boundary condition. Water and Al_2O_3 and TiO_2 nanoparticles with diameters of 35 nm and 50 nm, respectively, were used as working fluids. The experiments were performed for the Reynolds number between 500 and 4500, and for the nanoparticles concentrations of 0.25, 0.5, 0.75, and 1.0 vol.%. The results showed that for both tested nanofluids, the convective heat transfer coefficient and the pressure drop increases with increasing nanoparticle concentrations as well as Reynolds number, but Al_2O_3/water nanofluids showed more enhancements compared with TiO_2/water. Finally, two correlations for the Nusselt number and one correlation for the pressure drop were proposed:

Nusselt number correlations:

- for TiO_2/water nanofluids:

$$Nu = 0.5 He^{0.522} Pr^{0.613} \phi^{0.0815} \quad (3)$$

- for Al_2O_3/water nanofluids:

$$Nu = 0.7068 He^{0.514} Pr^{0.563} \phi^{0.112} \quad (4)$$

applicable in the range: $0.25\,\% < \phi < 1.0\,\%$, $115.3 < He < 1311.4$, $5.89 < Pr < 8.95$.

Pressure drop correlation:

$$\Delta p = 5.584 He^{1.36} \phi^{0.446} d_p^{0.163} \quad (5)$$