EXPERIMENTAL AND NUMERICAL INVESITGATION ON TURBULENT FLOW OF MULTIWALL CARBON NANOTUBE-WATER NANOFLUID INSIDE VERTICAL COILED WIRE INSERTED TUBES

by

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In this paper, heat transfer and pressure drop behavior of multiwall carbon nanotube-water nanofluid turbulent flow inside vertical coiled wire inserted tubes with constant heat flux boundary condition were investigated experimentally and numerically. In the experimental section, plain and five wire coils inserted tubes were used as the test sections geometries. In the numerical section, the governing equations associated with the required boundary conditions were solved using finite volume method based on the SIMPLE technique. The standard k- ε turbulence model was used in order to simulate the turbulence flow. The great agreement was found between the obtained experimental and numerical data with those predicted by the classical correlations for heat transfer and pressure drop in the plain tube. After validating the achieved data, the effects of various ranges of Reynolds number, particle weight concentration, wire diameter and coil pitch ratio on heat transfer coefficient and performance evaluation criterion were declared. It was concluded that the Nusselt number has been increased up to 102% at the highest Revnolds number inside the coil wire WC3. Moreover, the maximum enhanced performance evaluation criterion was seen for the wire coil with lowest coil pitch-to-tube inner diameter ratio (p/d) and highest wire-to-tube diameter ratio (e/d).

Key words: heat transfer, pressure drop, multiwall carbon nanotube, coil wire inserted tube

Introduction

In the past decades, many different techniques have been utilized in various energy providing devices to improve the poor thermal performance of conventional heat transfer fluids such as water or ethylene glycol which are widely used in many industrial cooling or heating applications. Among these techniques, the use of metallic or non-metallic nanoparticles of higher thermal conductivity as an additive suspended into the fluid is a technique that has been extensively employed for improving the heat transfer rate in many engineering equipment.

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In this regard, Choi [1] was one of the first researchers to develop a solid-liquid twophase mixture consisting of engineered nanometer-sized particles suspended in a base liquid to which he called nanofluid. Due to various benefits of the application of nanofluids such as improved rate of heat transfer, size reduction, and miniaturization of heat transfer system as well as minimal clogging, a large number of studies have been conducted both experimentally and numerically to determine the convective heat transfer characteristics of nanofluids in laminar and turbulent flow regimes. Wen and Ding [2] observed experimentally 47% heat transfer enhancement for Al₂O₃-distilled water nanofluid with 1.6 vol.% concentration flowing through a Cu tube in the laminar flow. Wang *et al.* [3] investigated on convective heat transfer of carbon nanotube (CNT)-water nanofluid in a horizontal tube, experimentally. They observed 70% heat transfer enhancement with 0.05% volume concentration of CNT-water nanofluid for a Reynolds number of 120. In a similar study, turbulent convective heat transfer and pressure drop of very dilute CuO/water nanofluid flowing through a circular tube was investigated experimentally by Fotukian and Esfahany [4]. Their results showed that the convective heat transfer increased by 25% while the pressure drop was 20% higher than that of pure water.

In addition to experimental studies, a good amount of nanofluids researches is dedicated to numerical investigation of the heat transfer features of nanofluids [5-9]. Also, different procedures are employed to perform the simulations, where the main choice is between single phase model with enhanced fluid properties and multi-phase models. However, the most popular multi-phase models include mixture model, dispersion model and the discrete phase model (Euleriane-Lagrangian interaction). Akbarinia and Laur [10] numerically studied the effect of particles diameter on laminar flow of nanofluids inside a curved tube. They used the two phase approach and control volume technique. Their research showed that the increase of the diameter of nanoparticles does not affect the flow behavior. Moghari *et al.* [11] investigated numerically the laminar mixed heat transfer convection of Al_2O_3 -water nanofluid in annulus using two phase approach. They observed that increasing nanoparticle volume fraction increases the Nusselt number while it does not have considerable influence on pressure drop.

The thermal performance of heat transfer systems can also be improved by other heat transfer enhancement passive techniques such as twisted tapes, wire coil inserts and helical screw tapes. Among these, coiled wire insert has been extensively used in several heat transfer applications including heat recovery processes, air conditioning and refrigeration systems, chemical reactors, etc. Due to noticeable advantages of wire coils over the other enhancement techniques such as low cost, simple manufacturing and easy to insert and removal from the tube, numerous investigations have been performed to study the effect of coiled wire inserts on heat transfer and friction factor. Garcia et al. [12] studied experimentally the laminar-transition-turbulent heat transfer enhancement and flow patterns in the tube with wire coil inserts. They reported that the heat transfer can be increased by 200% for coiled wire inserted tubes under transition flow regime. Akhavan-Behabadi et al. [13] conducted experiments to study the pressure drop and heat transfer augmentation due to coiled wire inserts during laminar flow of engine oil inside a horizontal tube. They observed 2.3 fold enhancement in Nusselt number for the specified coil insert compared to that of the plain tube. Prasad and Shen [14] investigated the enhancement of heat transfer by using twelve coil wire inserts in turbulent flow regime based on exergy analysis. However, there was found a few numerical investigations in the literature regarding the heat transfer characteristics of coil wire inserts.

Review of existing literature shows that in the published researches by the authors, the heat transfer and pressure drop characteristics of multiwall CNT-water (MWCNT)--water nanofluid turbulent inside vertical coil wire inserted tubes has not been comprehen-

sively examined both experimentally and numerically. In this research, a comprehensive experimental and numerical study has been performed to elucidate the impact of different parameters such as Reynolds number, particle weight concentration, wire diameter, and coil pitch ratio on Nusselt number and performance evaluation criterion (PEC). Consequently, the optimum performance of MWCNT-water nanofluid flow inside coiled wire inserted tubes is determined in terms of geometrical parameters and fluid flow characteristics.

Experimental procedure

Experimental apparatus

The schematic view of experimental apparatus and the test section developed to evaluate the convective heat transfer and friction factor characteristics during flow of MWCNT-water nanofluids through the tubes with coil wire inserts is shown in figs. 1 and 2, respectively. The flow loop consists of the test section, reservoir, centrifugal pump, cooler, flow measuring apparatus, flow controlling system, thermocouples, and differential pressure transmitter. In order to conduct experiments over a wide range of system variables, a plain tube and five wire coil inserted tubes were used as test sections.



Figure 1. Schematic diagram of experimental set-up

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Figure 2. Test section with wire coil insert and axial location of thermocouples [mm]

The test section is made of a Cu tube of 8.82 mm inner diameter, 9.52 mm outer diameter, and 1500 mm long. Wire coil inserts are manufactured from stainless steel wire. The geometrical parameters of coil wire inserted tubes and ranges of experimental operating parameters are presented in tabs. 1 and 2, respectively. In addition, more details about experimental procedure are described in [15].

Tube set	<i>d</i> [mm]	<i>p</i> [mm]	<i>e</i> [mm]	d_h [mm]	p/d	e/d
WC1	8.82	15	1	7.1195	1.70	0.113
WC2	8.82	20	1	7.4869	2.27	0.113
WC3	8.82	15	1.5	6.3529	1.70	0.170
WC4	8.82	25	1	7.7237	2.83	0.113
WC5	8.82	15	1.2	6.8075	1.70	0.136

Table 1. Characteristic dimensions of the wire coil inserted tubes

 Table 2. The ranges of operating parameters in present study

Nanoparticles weight concentration [%]	0.05, 0.1, and 0.2
Heat flux, [Wm ⁻²]	45000
Reynolds number	10000-20000
Mass flow rate, [kgs ⁻¹]	0.056-0.112

Due to hydrophobic surface of MWCNT, functionalization of CNT is applied in this study to prepare stable, homogenous and durable suspension of MWCNT--water nanofluids. Therefore, to add COOH functional groups to the purified MWCNT samples, CNT were dispersed in deionized water by using an ultrasonic water bath (KQ2200DE Ultrasonic Cleanser, 100 W,

Equipment Company, Italy), for 60 min at room temperature. Then potassium persulfate, KPS, was added as an oxidant to the flask and the pH of the reaction system was adjusted to 13 by adding potassium hydroxide solution. The flask with a reflux condenser and a magnetic stir bar was kept at 85 °C for 3 hours, and then it was naturally cooled to ambient temperature. The con-

tents of the flask were separated through a micro filter and washed with distillated water to become neutral. Finally, the products were dried overnight at 85 °C. Using this method, the stable nanofluids with three different nanoparticle weight concentrations of 0.05, 0.1, and 0.20% was prepared. It should be noted that MWCNT nanofluids made in this way were found to be very stable for a period of two weeks without visually observable sedimentation or settling. The properties of employed nanoparticles and the method used to prepare nanofluids and measure the properties of nanofluids is the same discussed in [15]. Moreover, transmission electron microscopy (TEM) images of applied nanoparticles are shown in fig. 3.



Figure 3. The TEM images of applied nanoparticles to the base fluid

Uncertainty analysis

The uncertainty of the major heat transfer parameters has been conducted based on the method proposed by Kline and McClintock [16]. The maximum uncertainties of nondimensional parameters were found to be $\pm 3\%$ for Reynolds number, $\pm 4.2\%$ for Nusselt number, and $\pm 4.8\%$ for friction factor.

Numerical procedure

Geometrical configuration

The schematic diagram of the numerical model was shown previously in fig. 2. The diameter and length of the tube test section are d = 8.82 mm and L = 1500 mm. Moreover, the geometrical parameters of different inserted wire coils in the aforementioned tube were the same as experimental section.

Governing equations

The continuity, momentum, and energy equations are written, respectively, as follows [17, 18]:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho \overline{u_i' u_j'} \right]$$
(2)

$$\frac{\partial}{\partial x_i} (\rho u_i C_p T) = \frac{\partial}{\partial x_j} \left[(\lambda + \lambda_i) \frac{\partial T}{\partial x_j} \right]$$
(3)

where μ , u, u', λ , and λ_t are the fluid viscosity, axial velocity, fluctuated velocity, molecular thermal conductivity and turbulent thermal conductivity, respectively.

In order to model the turbulent shear stress $-\rho \overline{u'_i u'_j}$, the Boussinesq hypothesis was used to correlate this term to the mean velocity gradients:

$$-\rho \overline{u_i' u_j'} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$
(4)

The turbulent viscosity (*i. e.*, μ_i) is defined by:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

The standard k- ε turbulence model was used in order to simulate the turbulence flow. The turbulence kinetic energy (*i. e.*, k) and its rate of dissipation (*i. e.*, ε) are obtained from the following transport equations [19]:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_i}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon$$
(6)

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_i}{\sigma_{\varepsilon}} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}$$
(7)

where G_k and $\rho \varepsilon$ represent the generation and destruction rates of turbulence kinetic energy, respectively. The term G_k is formulated:

$$G_k = -\rho \overline{u_i' u_j'} \frac{\partial u_j}{\partial x_i} \tag{8}$$

he constant values for the turbulent quantities were chosen as [20]:

$$C_{1\varepsilon} = 1.44, \quad C_{2\varepsilon} = 1.92, \quad C_{\mu} = 0.09, \quad \sigma_{k} = 1.0, \quad \sigma_{\varepsilon} = 1.3$$
 (9)

Boundary conditions

Fully developed flow and constant temperature boundary conditions were considered at the inlet of the tube. The axisymmetric conditions for velocity and temperature were assumed at the tube axes. On the tube wall, no slip conditions were imposed for the momentum equation. Also, constant heat flux condition was specified for the energy equation with a value of $45,000 \text{ W/m}^2$.

Numerical solution

In the present study, the governing differential eqs. (1)-(3) were solved numerically by incorporating FLUENT, ANSYS 14.5 package using finite control volume approach based on SIMPLE technique. Also, the second order upwind scheme was used to solve the momentum and energy equations. Moreover, the geometries of the computational domains and the generated mesh were made with Gambit 2.4.6. A grid independency of the solution was done for all the case studies to ensure that the obtained results were not dependent to the adopted grid density. The optimum triangular mesh chosen for tube set WC2 had 2 182 452 nodes and 1 413 558 elements. The most suitable triangular mesh properties for other tube sets were calculated similarly which is presented in tab. 3. In addition, finer mesh is used by non-uniform mesh due to the importance of velocity and temperature gradient near the wall. Also, the convergent criterion for all the variables was set 10^{-5} .

Table 3. Mesh properties for different studied tube sets geometries

Tube set	WC1	WC2	WC3	WC4	WC5
Mesh type	Triangular	Triangular	Triangular	Triangular	Triangular
Optimum number of elements	1180244	1413558	1156462	1702388	1167168

Results and discussions

Results validation

In order to verify the reliability and exactness of the experimental system and numerical model, the obtained Nusselt numbers calculated using the experimental data and the numerical results for the flow of distilled water in the plain tube were compared with the Nusselt numbers predicted from the equation in Gnielinski [21] for the turbulent flow, given by:

$$Nu_{d} = \frac{\frac{f}{8(\text{Re}-1000)\,\text{Pr}}}{1+12.7\sqrt{\frac{f}{8}}\left(\sqrt[3]{\text{Pr}^{2}}-1\right)}$$
(10)

which is valid in the range of 0.5 < Pr < 2000 and $2300 < Re < 5 \times 10^6$. The friction factor, *f*, in eq. (10) is computed by [22]:

$$f = \frac{1}{\left(0.79\ln \text{Re} - 1.64\right)^2} \tag{11}$$

In addition, in order to investigate the accuracy of fluid flow measurements inside the tube, the experimental and numerical friction factor was compared with that determined from Blasius equation in [22]:

$$f = 0.316 \text{ Re}^{-0.25} \tag{12}$$

which is valid in the range of $\text{Re} < 30\ 000$. Figures 4 and 5 illustrate the comparison between experimental and numerical data with the afore mentioned correlations for Nusselt number and friction factor, respectively. As can be seen, a reasonable agreement is observed between the results of the present study and those well-known correlations in both figures.



Heat transfer results

Figure 6 depicts the variation of experimental and numerical Nusselt number vs. Reynolds number for 0.05, 0.1, and 0.2% MWCNT-water nanofluid inside coil wire inserted tubes with the same coil pitch and different wire diameters. The results obtained for plain tube are also plotted for comparison. As seen, the addition of MWCNT nanoparticles to the base fluid and increase in the Reynolds number have led to an increase in experimental and numerical data of Nusselt number.



Moreover, it is seen that the Nusselt number is higher for wire coils with higher wire diameters for almost all the Reynolds numbers and nanofluids weight concentration. The rea-

son is that inserting coil wire into the plain tube decreases the flow area, while velocity and its swirl vorticity augments along with the turbulence generated. As known, the swirl velocity induces centrifugal force which results in the heat transfer enhancement. The increment in the exposed surface area and turbulent mixing are other justifications. Therefore, maximum rate of heat transfer is obtained for WC3 with highest wire diameter.

The similar trend is observed in fig. 7 in which the variation of both experimental and numerical Nusselt number as a function of Reynolds number is plotted for the flow of nanofluids with different nanoparticle concentrations inside coil wire inserted tubes with the same wire diameter and different coil pitches. The maximum error was found to be 16% for WC4 with 0.05% MWCNT weight concentration.



In addition, it can be seen that higher Nusselt number is obtained for wire coils with lower coil pitches at the same range of Reynolds numbers for all nanofluids. Consequently, the maximum Nusselt number is for WC1 with the lowest coil pitch. This trend in Nusselt Number can be justified by the reduction in pitch length which results in decrease in the overall annulus length, or due to reduction of helical pitch. Increase in Nusselt number is attributed to increase in turbulence intensity and swirling flow.

Performance evaluation criterion

In order to find the optimum work conditions, a further study on the overall performance were carried out bases on performance index, η , which is defined [23]:

$$\eta = \frac{\frac{\mathrm{Nu}^{*}}{\mathrm{Nu}_{PT,BF}}}{\sqrt[3]{\frac{f^{*}}{f_{PT,BF}}}}$$
(13)

where Nu^{*} and f^* are, respectively, the Nusselt number and friction factor of the tube with enhancing factor (nanofluid and/or wire coil inserted tube), while Nu_{PT,BF} and $f_{PT,BF}$ represent the Nusselt number and friction factor of the base fluid inside plain tube.

Figure 8 depicts the effect of coil wire geometry on the PEC variation with Reynolds number at different nanoparticle weight concentration. As perceived, utilization of nanofluid along with the coil wire in plain tube enhanced the PEC more effectively. It can be deduced from this figure that the best heat transfer performance is achieved for the WC3 with lowest coil pitch-to-tube inner diameter ratio, p/d, and highest wire-to-tube diameter ratio, e/d, at different nanoparticle weight fractions and then it is followed by WC5, WC1, WC2, and WC4, respectively.



Figure 8. Effect of coil wire geometry on PEC variation with Reynolds number; (a) wt.% = 0,1, (b) wt.% = 0,2

Conclusions

Experimental and numerical investigations have been carried out to study the heat transfer and pressure drop behavior of MWCNT-water nanofluid turbulent flow inside vertical coiled wire inserted tubes with constant heat flux boundary condition. The achieved results for Nusselt number and friction factor had great agreement with those obtained by the classical correlations. In all cases, the numerical computation model could reasonably predict the experimental data in terms of both trend and quantity. It was observed that increase in the suspended nanoparticle weight fraction can enhance Nusselt number compared to the pure fluids due to the increment in the thermal conductivity of the mixture.

Moreover, inserting the coil wire into the plain tube has a remarkable impact on the Nusselt number and friction factor which significantly augment the amount of these parameters due to the swirl flow and turbulence augmentation produced in the gap between the wire and the cylinder inner surface. It was also indicated that the average Nusselt number enhancement of coiled wire inserted tubes varies from 1.29 to 2.02 times in comparison with those data form the plain tube at the considered range of Reynolds number.

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Another key finding of this research was investigating the effect of coil wire geometry on the Nusselt number and PEC parameters. It was concluded that heat transfer characteristics of the fluid are more influenced by the wire-to-tube diameter ratio, e/d, rather than the coil pitch-to-tube inner diameter ratio, p/d. Hence, the optimum performance was achieved for WC3 with lowest coil pitch-to-tube inner diameter ratio, p/d, and highest wire-to-tube diameter ratio, e/d. Moreover, effect of coil wire geometry was shown to be more prominent than the effect of nanofluid weight concentration on the heat transfer.

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