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An experimental study on heat transfer and pressure drop of MWCNT–water nano-fluid inside horizontal coiled wire inserted tube ☆

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ABSTRACT

An experimental investigation has been carried out to study the heat transfer and pressure drop characteristics of Nanofluid turbulent flow inside horizontal copper tube with different wire coil inserts under constant heat flux. The plain and coil inserted tubes were used as the test section's geometries and were heated by an electrical coil heater to produce constant heat fluxes. Nanofluids with different particle weight concentrations of 0.05%, 0.1%, and 0.2% were prepared by dispersion of functionalized multi-walled carbon nanotubes (MWCNTs) in distilled water and stabilized by means of an ultrasonic device. The effect of different parameters such as Reynolds number, nano-particle concentration, wire diameter and coil pitch on heat transfer coefficient and pressure drop are studied. Observations clearly show that for a specific nanoparticle concentration, increase in both heat transfer and pressure drop is obtained by inserting coil wires. In average, 85% increase in heat transfer coefficient and 475% penalty in pressure drop was observed at the highest Reynolds number inside the wire coil inserted tube with the highest wire diameter. Finally, two new correlations are introduced using the results of the experiments for predicting the Nusselt number and friction factor of the nanofluid flow inside coiled wires inserted tubes.

1. Introduction

Conventional fluids such as water, ethylene glycol, engine oil and transformer oil are commonly used in single-phase forced convection heat transfer applications to prevent the overheating or to improve heat transfer rate of different equipment in many industrial sectors including power generation, chemical production, air-conditioning, transportation and microelectronics. Due to poor heat transfer properties of these common fluids; in particular their thermal conductivity, many researchers have focused their effort on development of high performance heat transfer fluids in the past few decades. One of the recent methods used is to add nanoparticles of highly thermally conductive material like carbon, metal and metal oxides into heat transfer fluids to improve the overall thermal conductivity. Choi [1] was the first one who used the term nanofluid to specify uniformly dispersed and suspended nanometer-sized particles inside a liquid. Excellent properties of nanofluids such as enhanced thermal conductivity, long time stability and noticeable convective heat transfer enhancement as well as little penalty in pressure drop increment have motivated many researchers to investigate the heat transfer performance and flow characteristics of various nanofluids with different nanoparticles and base fluid materials. Ding et al. [2] built an experimental system to investigate the convective heat transfer of CNT nanofluids in laminar regime with a constant heat flux wall boundary condition. They observed a maximum enhancement of 350% in convective heat transfer coefficient of 0.5 wt.% CNT/water nanofluid at $Re = 800$. In a similar study, Wang et al. [3] obtained 70% and 190% heat transfer enhancement with 0.05% and 0.24% volume concentration of CNT–water nanofluid in a horizontal tube for a Reynolds number of 120. Ferrouillat et al. [4] observed 10% to 60% heat transfer enhancement for SiO_2–water in the weight concentration of 5% to 34% for the Reynolds number range of $200 < Re < 10{,}000$. Asirvatham et al. [5] investigated on convective heat transfer of silver nanofluid in a turbulent flow condition. They observed 28.7% and 69.3% heat transfer enhancement with 0.3% and 0.9% volume concentration of silver–water nanofluid. Turbulent heat transfer behavior of TiO_2/water nanofluid in a circular pipe under the constant wall temperature condition was investigated by Sajadi and Kazemi [6]. They reported that the heat transfer coefficient increased about 22% at a concentration of 0.25 vol.% for a Reynolds number of 5000, while the pressure drop was about 25% greater than that of pure water. Fotukian and Nasr Esfahany [7] carried out an experimental study on turbulent convective heat transfer performance and pressure drop of very dilute CuO/water nanofluid flowing through a circular tube. They observed 25% and 20% heat transfer and friction factor enhancements with 0.03 vol.% concentration. Another passive technique which is employed to augment flow heat transfer rate is using coiled wire inserted tubes instead of round tubes. The rate of heat transfer enhancement depends on flow conditions and geometry of the inserts. Garcia et al. [8] argued that

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Nomenclature

C_p	Specific heat of fluid [J /kg K]
d	Tube inside diameter [m]
d_h	Hydraulic diameter, [-] $d_h = 4$ * (free volume/wetted surface) [m]
d_c	Wire coil diameter [m]
e	Wire diameter [m]
f	Friction factor
h	Heat transfer coefficient [W/m^{2}K]
k	Fluid thermal conductivity [W/mK]
L	Tube length [m]
$\dot{m}$	Mass flow rate [Kg/ s]
Nu	Nusselt number, [-] Nu = hd/k
ΔP	Pressure drop [pa]
P	Perimeter of tube [m]
Pr	Prandtl number, [-] Pr = $C_p\mu/k$
q''	Heat flux [W /m^2]
Q	Heating rate by electric heater [W]
Re	Reynolds number, [-] Re = ρvD/μ
T	Temperature [°C]
T_w	Wall temperature [°C]
T_b	Bulk temperature [°C]
V	Velocity [m/s]
Wt	Weight fraction

Greek symbols

μ	Fluid dynamic viscosity [kg /m s]
ν	Fluid kinematic viscosity [m^2/s]
ρ	Fluid density [kg/ m^3]
φ	Particle weight concentration [%]

Subscripts

B	Bulk
Bf	Base fluid (water)
Exp	Experimental
F	Fluid
In	Inlet
Nf	Nano-fluid
Out	Outlet
P	Particle
Th	Theory
W	Wall

wire coils can increase heat transfer in two possible ways. They may generate swirling in the flow or turbulence can be created by separation and reattachment mechanism of the fluid passing over the coil. Additionally, a better physical contact of the coil with the tube wall may also lead to a better conduction. They also reported that coiled wire inserted tubes perform better than the smooth tube in laminar to low turbulent flow range. Furthermore, the transition range is the best working range for wire coils where heat transfer can be increased by 200%. The effects of wires with square cross section forming a coil used as a turbulator on the heat transfer enhancement in a circular tube under uniform heat flux are introduced by Promvonge [9]. He showed that the use of coiled square wire turbulators leads to a remarkable increase in heat transfer and friction factor compared to those of a smooth tube. Naphon's [10] investigation was designed to examine the influences of coil pitch and other related parameters on heat transfer enhancement and pressure loss in horizontal double tubes with coiled wire inserts. His experimental results showed that the coiled wire inserts are especially effective on laminar flow regime in the meaning of heat transfer enhancement. Chandrasekar et al. [11] observed 21.5% heat transfer enhancement with wire coiled insert pitch of 3 for 0.1% of Al_2O_3/water nanofluid in a tube under fully developed laminar flow. Akhavan-Behabadi et al. [12] studied six coiled wires by using engine oil as test fluid to study the enhancement in heat transfer coefficient inside a horizontal tube. They obtained 2.3 fold enhancement in Nusselt number for the specified coil insert compared to that of the plain tube. Furthermore, two empirical correlations have been developed for predicting the heat transfer enhancement of those coiled-wire inserts. Naik and Sundar [13] conducted experiments for propylene glycol and water based CuO nanofluid flowing in a tube with helical coil inserts and proposed two correlations for Nusselt number and friction factor. Kahani et al. [14] experimentally probed the heat transfer behavior of Al_2O_3/water and TiO_2/water nanofluid flowing in a tube with helical coil inserts for Reynolds number ranging from 500 to 4500 and particle volume concentrations up to 1.0%. Sundar and Singh [15] reviewed and provided the existing correlations for different type of nanofluid flowing in a tube with different kind of inserts. Review of existing literature reveals that only a few articles have considered the simultaneous effects of adding nanoparticles and using wire coil inserts on heat transfer and pressure drop inside horizontal tubes. In the present work, heat transfer and pressure drop characteristics of MWCNT/water nanofluid turbulent flow is studied experimentally inside both coiled wire tubes and plain tubes submitted to a uniform heat flux on its outside surface. All physical properties of MWCNT/water nanofluids needed to calculate the pressure drop and the convective heat transfer coefficient are measured experimentally as a function of volume concentration and temperature; in addition, Nusselt number and friction factor correlations were proposed based on the experimental data.

2. Nanofluid preparation

Deionized water and multi-walled carbon nanotubes (MWCNTs) were used to produce nanofluids. MWCNTs were produced by chemical vapor deposition (CVD) process at the Research Institute of Petroleum Industry (RIPI) (Tehran, Iran). Properties of the applied nanoparticles to the base fluid are described in Table 1. The SEM (Scanning Electron Microscope) micrograph of the CNT nanoparticles and Raman analysis pattern are shown in Figs. 1 and 2, respectively. Due to hydrophobic surface of MWCNTs, many efforts and numerous procedures have been made to prepare stable, homogenous and durable suspension of MWCNT–water nanofluid, using various surfactants [16] or chemical functionalization [17]. For better stability, functionalization of carbon nanotubes is applied in this study. Therefore, to add COOH functional groups to the purified MWCNTs samples, carbon nanotubes were dispersed in deionized water by using an ultrasonic water bath (KQ2200DE Ultrasonic Cleanser, 100 W, Equipment Company, Italy) for 60 min at ambient temperature. Then potassium persulfate (KPS) as oxidant was added to the flask and the pH of the reaction system adjusted by potassium hydroxide solution. The flask with a reflux condenser and a magnetic stir bar was kept at 85 °C for 3 h, and then it was naturally cooled to room temperature. The contents of the flask were separated through a micro filter and washed with distillated water to become neutral. Finally, the products were dried overnight at

Table 1
Properties of the nanoparticles (MWCNT).

Parameter	Value
Purity	95%
Outer diameter (nm)	5–20
Inner diameter (nm)	2–6
Thermal conductivity (W/m^{2}K)	1500
Number of walls	3–15
Apparent density (g/cm^3)	0.15–0.35
Specific heat capacity (J/kg K)	630
Loose agglomerate size (mm)	0.1–3