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Experimental study on heat transfer and pressure drop of nanofluid flow in a horizontal coiled wire inserted tube under constant heat flux

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ABSTRACT

In this work, an extensive experimental study has been carried out to investigate the heat transfer and pressure drop characteristics of CuO/Base oil nanofluid laminar flow in a smooth tube with different wire coil inserts under constant heat flux. The nanofluid is prepared by dispersion of CuO nanoparticles in base oil and stabilized by means of an ultrasonic device. Particles volume fraction is ranging from 0.07% to 0.3%. Five coiled wires having pitches of 25–35 mm and wire diameters of 0.9–1.5 mm were put one by one in the test section. The effect of different parameters such as Reynolds number, wire diameter, coil pitch, nanofluid particles concentration and heat flux on heat transfer and friction factor are studied. The experimental results clearly indicate that for a specific nanoparticle concentration, increase in both heat transfer and pressure drop is obtained by inserting coil wires. In average, 45% increase in heat transfer coefficient and 63% penalty in pressure drop was observed at the highest Reynolds number inside the wire coil inserted tube with the highest wire diameter. Since the applied heat transfer enhancement techniques are accompanied by increase in flow pressure drop, the overall performance of these techniques is evaluated at different Reynolds number. Finally, two empirical correlations are developed for predicting the Nusselt number and friction factor of the nanofluid flow insidecoiled wires inserted tubes. These correlations predict the experimental data in an error band of (±20%).

1. Introduction

Heat transfer fluids such as water, oil and ethylene glycol are widely used to prevent the overheating or to improve heat transfer rate of different equipments. But, the poor heat transfer properties of these fluids compared with those of most solids are the primary hindrance of high compactness and the effectiveness of the heat exchangers. Therefore, many researchers have focused their effort on development of high performance heat transfer fluids in the past few decades. In the early researches, suspension and dispersion of millimeter or micrometer-sized particles were employed. However, heat transfer fluids containing suspended particles of micro/millimeter sizes suffered from numerous drawbacks like erosion of the components by abrasive action, clogging in small passages, settling of particles and increased pressure drop. Nanofluid is a new class of fluid for improving both thermal conductivity and suspension stability in the various industrial fields. It is consisting of uniformly dispersed and suspended nanometer-sized particles which were first pioneered by Choi [1] in 1995.

Faulkner et al. [2] investigated on convective heat transfer of Carbon nanotubes–Water nanofluid in fully developed laminar flow region. They observed significant increase in heat transfer. They reported that heat transfer coefficient increases with rise in Reynolds number. Also, they mentioned that nanofluids with lower volume concentration (1.1%) had better performance instead of nanofluids with higher concentrations (2.2% and 4.4%). Wen and Ding [3] reported experimental results for the convective heat transfer of γ-Al_2O_3 (27–56 nm)/water based nanofluids flowing through a copper tube in laminar regime. They found that the inclusion of Al_2O_3 particles can significantly enhance the convective heat transfer coefficient, which increases with increasing particle concentrations. Furthermore, the improvement of the heat transfer coefficient was particularly significant in the thermal entrance region. They also showed that the length of thermal entrance region for nanofluid was more than that of pure water.

A review of convective heat transfer enhancement with nanofluids is presented by Kakaç and Pramuanjaroenkij [4]. However, there are just a few studies which have considered the increased amount of nanofluid pressure drop besides their heat transfer enhancement.

Xuan and Li [5] investigated on convective heat transfer coefficient and friction factor of nanofluids for both laminar and turbulent flow in a tube. The nanofluid used in their study was deionized water with a dispersion of Cu particles of below 100 nm diameter. According to them, for the nanofluid with 2.0 vol.% concentration, the convective heat transfer coefficient of Cu/water nanofluid is

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Nomenclature

A_m	constant value
Cp	specific heat (J/kg K)
d	inside diameter (m)
d_h	hydraulic diameter $4 \times$ (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	thermal conductivity (W/m K)
L	tube length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
P	perimeter of tube (m)
p	wire coil pitch (m)
Pe	Peclet number
q''	heat flux (W/m^2)
Q	heating rate by electric heater (W)
Pr	Prandtl number
$R3$	performance evaluation factor
Re	Reynolds number
T	temperature (°C)
x	distance from the pipe inlet (m)
x^+	non-dimensional parameter

Greek symbols

ρ	density (kg/m^3)
ϕ	volume fraction
μ	dynamic viscosity (Pa s)
ΔP	pressure drop (Pa)
γ_m	eigenvalue
η	heat lost factor

Subscripts

f	base fluid
in	inlet
m	bulk
nf	nanofluid
p	plain tube
out	outlet
s	tube surface
wc	coil wire inserted tube
x	local

increased about 60%. Their pressure drop studies for both the laminar and the turbulent flow revealed no significant augmentation in pressure drop. This indicates that the nanofluids will not cause extra penalty in pump power.

An experimental study on forced convective heat transfer and flow characteristics of a nanofluid consisting of water and 0.2 vol.% TiO_2 nanoparticles in a double-tube counter flow heat exchanger was reported by Duangthongsuk and Wongwises [6]. They utilized the Degussa P25 TiO_2 nanoparticles of about 21 nm diameter. They concluded that the convective heat transfer coefficient of nanofluid is slightly higher than that of the base liquid by about 6–11%. Also, their study showed that the heat transfer coefficient of the nanofluid increases with an increase in the mass flow rate of the hot water and nanofluid, and it is increased with a decrease in the nanofluid temperature. The temperature of the heating fluid had no significant effect on the heat transfer coefficient of the nanofluid. Finally, they obtained that the use of nanofluid instead of base fluid has a little penalty in pressure drop.

Recently, the heat transfer characteristics and pressure drop of very dilute (less than 0.24 vol.%) CuO/water nanofluid flowing in a circular tube with constant wall temperature under turbulent regime condition was reported by Fotukian and Nasr Esfahany [7]. They observed that addition of small amounts of nanosizedCuO particles to the base fluid increased the heat transfer coefficients, considerably. They observed an average of 25% increase in heat transfer coefficients. Also, their study showed that the pressure drop of the flow did not necessarily increase with the increase in nanoparticles concentration. The maximum increase in pressure drop was about 20% for nanofluid with 0.03 vol.% concentration.

Another technique which is used to augment flow heat transfer rate is using wire coil inserts fitted inside the tube. Wire coil inserts are devices whose reliability and durability are widely contrasted [8]. The rate of heat transfer enhancement is dependent on flow conditions and wire coil geometry. However, it is expected that wire coils will act as artificial roughness at high Reynolds numbers.

Webb [9], Ravigururajan and Bergles [10] concluded that in turbulent regime, wire coils disturb the flow in a similar way that corrugated or ribbed tubes do. Also, Kumar and Judd [11] tested 15 wire coils by using water as a base fluid. They observed remarkable increase in Nusselt number by using wire coils. Also, Uttarwar and Raja Rao [12] and Inaba et al. [13] studied on wire coils inserted tubes for laminar and transition flows. Rabas [14] compiled friction factor data taken from several sources for single phase turbulent flow inside tubes with wire coil inserts. He concluded that there was no obvious explanation to select any of the available friction factor correlations.

Garcia et al. [15] carried out an experimental study on heat transfer enhancement with six different wire coils in laminar-transition-turbulent regimes at different Prandtl numbers. Experimental correlations were provided for friction factor and heat transfer of the turbulent flow at Reynolds numbers above 2000 and 1700, respectively. In addition, Results showed that in turbulent flow, wire coils increase pressure drop up to nine times and heat transfer up to four times compared to those of smooth tube without wire coils. At low Reynolds numbers, flow inside the tubes with wire coils behaves like the one inside the smooth tube but is accelerating towards the transition regime at Reynolds numbers as low as 700 due to the presence of wire coils. Within the transition region, if wire coils are fitted inside a smooth tube heat exchanger, heat transfer rate can be increased up to 200% keeping pumping power constant.

The heat transfer characteristics and the pressure drop of the horizontal double pipe with coil-wire insert were investigated by Naphon [16]. Cold and hot water were used as working fluids in the shell side and tube side, respectively. He showed that coil-wire insert has significant effect on the enhancement of heat transfer especially in laminar flow region. Promvonge [17] reported the effects of wires with square cross section forming a coil used as a turbulator on the heat transfer and turbulent flow friction characteristics in a circular tube under uniform heat flux. His experimental results revealed that the use of coiled square wire turbulators leads to a considerable increase in heat transfer and friction factor compared to those of a smooth tube.

Akhavan-Behabadi et al. [18] carried out an experimental investigation to study the enhancement in heat transfer coefficient by coiled wire inserts during heating of engine oil laminar flow inside a horizontal tube. They used seven coiled wire inserts having