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# Convective Heat Transfer Enhancement of CNT-Water Nanofluids in Plain Tube Fitted with Wire Coil Inserts

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## Abstract
*The turbulent convective heat transfer and pressure drop characteristics of CNT-water nanofluid in a horizontal tube fitted with wire coil inserts are studied experimentally. CNTs were synthesized by chemical vapor deposition (CVD) method with purity of more than 99%, functionalized by acid treatment and dispersed in distilled water in different concentrations. Also, the thermal conductivity and viscosity of synthesized nanofluids were measured experimentally. Convective heat transfer experiments are conducted with water and nanofluids in the range of 5000 < Re < 22000, CNT volume concentration 0 <* $\varphi$ *< 0.1 % and wire coil with wire pitch of 2. The experimental results indicate that the convective heat transfer increases up to 23% in 0.05 vol% CNT-nanofluid and the heat transfer coefficient increases with CNT vol% and Reynolds number. Wire coil inserts increase the heat transfer coefficient of water and nanofluids up to 102% in Re=5700 but its performance decreases with Reynolds number. Experiments have shown that only use of wire coil inserts increases pressure drop of working fluid. Moreover, empirical correlations for Nusselt number and friction factor are proposed from nonlinear regression of the experimental data. Further, performance evaluation of enhanced tube is determined with considering opposing thermal resistance.*

**Keywords:** *CNT, Nanofluid, Heat Transfer Coefficient, Wire Coil Inserts*

## 1. Introduction
From the past decades, researchers have studied development of enhancement techniques to reduce the size and costs of heat exchangers. Use of wire coil inserts, twisted tape inserts and other mechanical turbulators is one of the passive methods that change hydrodynamics and increase turbulence of the working fluid that leads to higher heat transfer coefficient [1-4]. Another passive method is based on change of the thermo-physical properties of heat transfer fluids such as water, ethylene glycol and oil. Recently, addition of nanoparticles such as carbon nanotubes (CNTs), $Al_2O_3$ and CuO to conventional heat transfer fluids called nanofluids is considered. Nanofluids commonly have potentials in heat transfer enhancement applications because of their interesting properties such as considerable increase in thermal conductivity, long term stability, and prevention of erosion and

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clogging in microchannels due to smaller size and larger interface area compared with micrometer-sized particles [5-8]. CNTs are excellent candidates as dispersions for preparing nanofluids, due to their very high thermal conductivity and very large aspect ratio [8]. Pak and Cho [9] studied $TiO_2$-water and $Al_2O_3$-water nanofluids in turbulent convective heat transfer inside tubes. Yang *et al*. [10] studied laminar convective heat transfer of graphite nanofluids in a horizontal tube heat exchanger. Xuan and Li [11] considered convective heat transfer and flow features of CuO-water nanofluids. Wen and Ding focused on entry region under laminar flow condition using nanofluids containing $Al_2O_3$ and CNTs in horizontal tube [12, 13]. Ding *et al*. [14] reported significant enhancement in convective heat transfer of multi-wall carbon nanotube dispersion in water and found that amount of enhancement depends on the Reynolds number, CNT concentration, and pH. Xing *et al*. [15] found the laminar heat transfer enhancement of 70% and 190% for nanofluids containing 0.05 and 0.24 *vol%* CNT in water at Re=120. Also, Rashidi *et al*. [16] experimentally investigated heat transfer enhancement of CNT–water nanofluids in a horizontal shell and tube heat exchanger in laminar flow. They found an increase of overall heat transfer coefficient with Reynolds number.

Using nanofluids and tube inserts together in horizontal tubes is considered by several researchers. Heat transfer enhancement for $Fe_3O_4$ nanofluid in a tube with twisted tape inserts has been experimentally investigated by Sundar *et al*. [17]. They found that 30.96% enhancement for 0.6 *vol*% of $Fe_3O_4$ in a plain tube and further enhancement of 18.49% in a plain tube with twisted tape (H/D=5) at the Re = 22000. The heat transfer enhancement of 23.69% for 0.1 *vol%* of $Al_2O_3$ nanofluid in a tube has been analyzed by Sharma *et al*. [18]. Further 44.71% heat transfer enhancement is observed with twisted tape insert with (H/D=5) inside a circular tube at Re = 9000. Sundar and Sharma [19] have observed 30.30% heat transfer enhancement for 0.5% of $Al_2O_3$ in a plain tube, further, 42.71% of heat transfer enhancement with twisted tape (H/D=5) is observed compared to water at Re = 22000. Laminar flow of CuO/base oil nanofluid in a tube with wire coil inserts has been estimated by Saeedinia *et al*. [20] experimentally and 45% enhancement was noted in heat transfer for 0.3 *vol% CuO*. Fully developed laminar flow of 0.1 *vol%* $Al_2O_3$ nanofluid in a tube with wire coil inserts has been analyzed by Chandrasekar *et al*. [21] who observed 21.53% heat transfer enhancement with wire coil pitch of 3. Noticeable increase of pressure drop of the nanofluids with inserts was found in all above-mentioned researches. Jafari Nasr *et al*. [22] investigated performance evaluation of heat transfer enhancement tubes fitted with turbulator devices such as twisted tape, wire coiled and so on. They developed a new performance index taking into consideration the effect of opposing thermal resistances such as fouling. Their results showed that the potential benefits of heat transfer enhancement cannot be analyzed from the effects of thermal resistances separately.

As mentioned above, inserts could enhance convective heat transfer of nanofluids and no work has been done on CNT-water nanofluids in turbulent regime. Therefore the aim of this paper is based on investigation of turbulent heat transfer enhancement and pressure drop in a horizontal tube with constant heat flux using combination of CNT-water nanofluids and wire coil inserts. Also, the performance evaluation of enhanced tube with nanofluids and wire coil inserts are considered.

## 2. Experimental

### 2-1. Experimental system

The experimental system for measuring the convective heat transfer coefficient is shown schematically in Fig. 1. It mainly consists of a test section, a centrifugal pump, a reservoir tank, and a cooling part. A straight copper tube of 1100 *mm* length, 12.2 *mm* ID and 15.8 *mm* OD is used as the test section. An electrical heater wire with maximum power of 2000 W was adopted to supply a constant heat flux condition along the copper tube and a thick Rockwool insolating layer surrounded the heater to prevent heat loss from the test section. Seven K-type thermocouples were mounted on the test section in equally spaced distance to measure wall temperature along the tube and two thermocouples were inserted into the flow at the inlet and outlet of the heat transfer section to measure temperature of passing fluid. To achieve steady state conditions, outlet flow from test section is allowed to cool in a coil tube heat exchanger with cooling water. The liquid is forced through the test section with the aim of constant flow pump. Flow rate of inlet flow is controlled by a valve before test section and additional fluid is returned to reservoir tank through bypass line. To make hydrodynamically fully developed flow and to eliminate the entrance effects, outlet flow of pump is initially passed through 2 *m* straight tube in calming section before interring into the test section. Also, the volumetric flow rate of inlet liquid and fluid pressure drop are measured by magnetic flowmeter and U-tube mercury monometer, respectively.

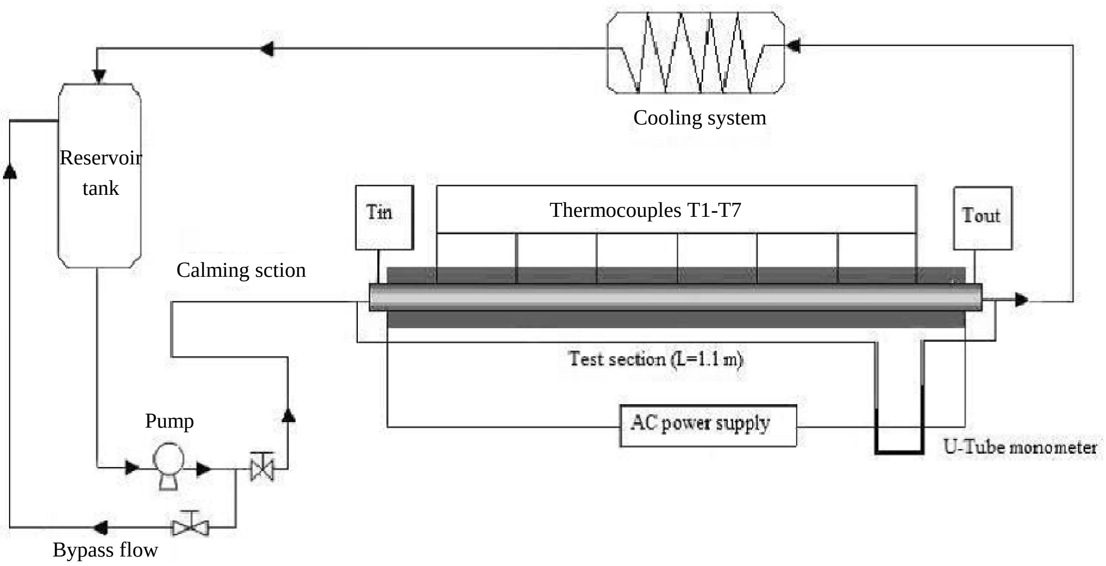



**Figure 1.** Experimental system for the measurement of convective heat transfer coefficient.

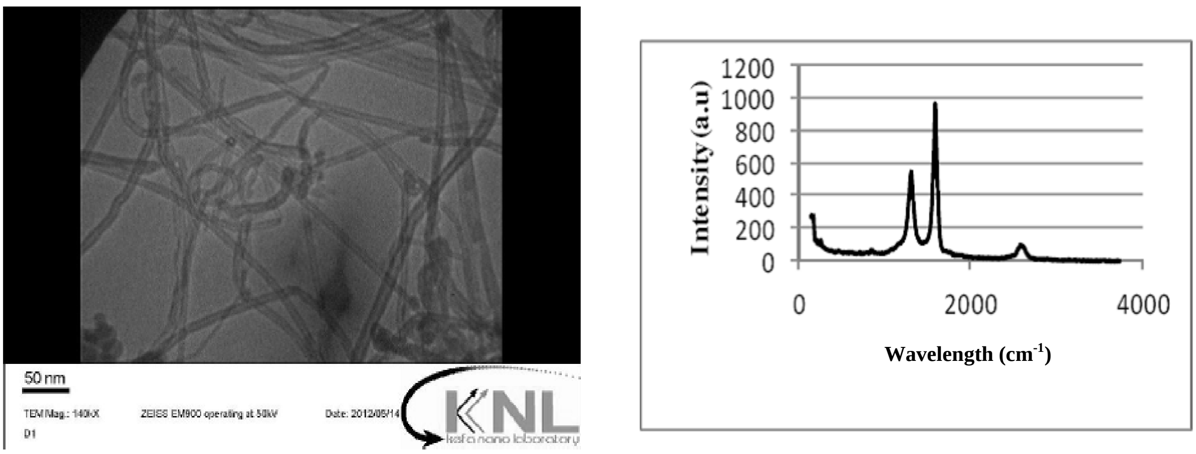
**2-2. Nanofluids preparation**

Distilled water (DW) and carbon nanotubes (CNTs) were used to produce nanofluids. Initially high purity CNTs were synthesized in Research Institute of Petroleum Industry (RIPI*)* by CVD process over Co-Mo, supported MgO nanostructured catalyst in 800-900 $^{\circ}C$, 45 min reaction time with methane as a carbon source and purity more than 99%. Fig. 2 shows TEM and Ramen spectroscopy of produced CNTs. The CNTs have average diameter and length of 10-20 *nm* and 10 $\mu m$ , respectively. It is found from Fig. 2 that the value of $I_G/I_D$ (Intensity of G-band over D-band) is about 2, which confirms the high quality of CNTs. Five samples of nanofluids were prepared by dispersing CNTs in DW with CNT concentration of 0.03, 0.05, 0.1, 0.15 and 0.2 by wt % (0.0142 – 0.095 *vol%*). Weight percent of CNTs in nanofluids can be converted to volume percent as follows:

$$\phi = \frac{\mathrm{wt}.\rho_f}{(1-\mathrm{wt})\rho_p + \mathrm{wt}.\rho_f} \tag{1}$$

Where wt is weight percent and $\rho_f$ and $\rho_p$ are density of DW and CNTs respectively. In this work $\rho_p$ is taken as 2.1 g/cm$^3$.

Because of hydrophobic surface of CNTs that lead to aggregation and precipitation in DW, CNTs are functionalized by acid treatment with mixture of nitric and sulfuric acid in a ratio of 1:3. By acid treatment hydrophilic functional groups such as C–O–C, C=O, and O–H might be introduced onto the CNTs surfaces, which leads to dispersing CNTs in DW [23]. It was found that CNTs are entangled and some are in the form of agglomerates. After addition of CNTs to DW, to disentangle nanotubes and to break agglomerates, nanofluids were ultrasonicated for 1 hour at 100% amplitude using a 100W, 40 kHz ultrasonic bath. CNT nanofluids made in this way were found to be stable for over 1 month with no visible sedimentation or settling.




**(a)** **(b)**

**Figure 2.** (a) TEM. (b) Ramen spectroscopy of produced CNTs.

## 3. Physical properties of nanofluids

### 3-1. Thermal conductivity

The thermal conductivity of nanofluids samples were measured using a KD2 Pro thermal properties analyzer (Decagon Devices, Inc., USA) in 25°C and 30°C with accuracy of 5%.The instrument was based on the working principle of a transient hot wire method. Initially, thermal conductivity of DW as a base fluid was measured by KD2 probe. For DW $k_w$ was obtained as 0.6 $W/m.k$ which proves the accuracy of KD2 instrument. Therefore thermal conductivity of each five samples was measured in two temperatures. Fig. 3 shows measured thermal conductivity ratio ($k_{nf}/k_f$) of nanofluids. As shown in this figure, the thermal conductivity of water was enhanced with increase of CNT *vol%* and temperature. Maximum enhancement of 25.5 % and 38.7% is achieved for 0.2 *wt%* (0.095 *vol%*) nanofluids in 25 °C and 30°C, respectively. Due to high purity of synthesized CNTs used in the experiments, this enhancement is noticeable in comparison with previous works done by researchers [5,13,14,24-26] on thermal conductivity of CNT-water nanofluids. More details of this work are presented by authors in previous work on thermal conductivity enhancement of CNT-water nanofluids [27]. The values of nanofluids thermal conductivity in Fig. 3 were used for each experiment of convective heat transfer.

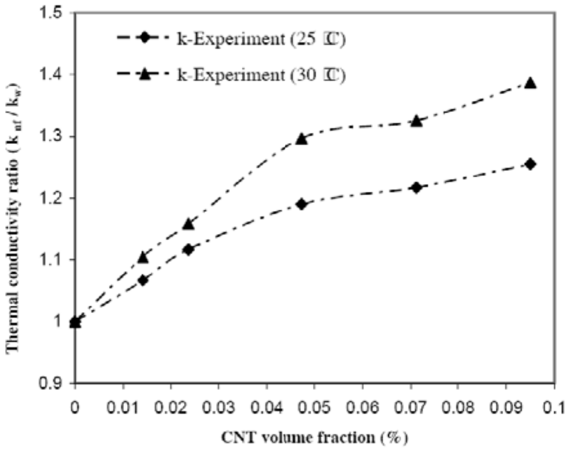



**Figure 3.** Thermal conductivity ratio of nanofluids to DW versus CNT *vol%* and temperature.

### 3-2. Viscosity

Because CNT *vol%* in samples is less than 0.1%, nanofluids could be assumed as Newtonian fluids. The viscosity of nanofluids samples was measured using Gallen Camp bath viscometer in 20, 30 and 40°C. In each experiment viscometer was filled with nanofluid and set in the bath to reach determinate temperature. Then the passing time of nanofluids between two indicators of viscometer was recorded by stop watch. This measured time was multiplied by viscometer constant to obtain viscosity of nanofluid.

Initially, to evaluate the accuracy of viscometer, viscosity of DW was measured in 20 °C. Obtained result for viscosity of DW was 1.0042 centi-stokes (1.0016 cP) which is in good agreement with the data in literature for DW in 20°C (0.98 cP) with a difference of about 2%. Thus viscosity of all nanofluid samples was measured by viscometer in 3 temperatures accurately. The results of nanofluids viscosity are shown in Fig. 4. In heat transfer calculations, viscosity of nanofluids is taken from Fig. 4.

### 3-3. Specific heat and density

To determine specific heat and density of nanofluids, the following relations in literature were used [28];

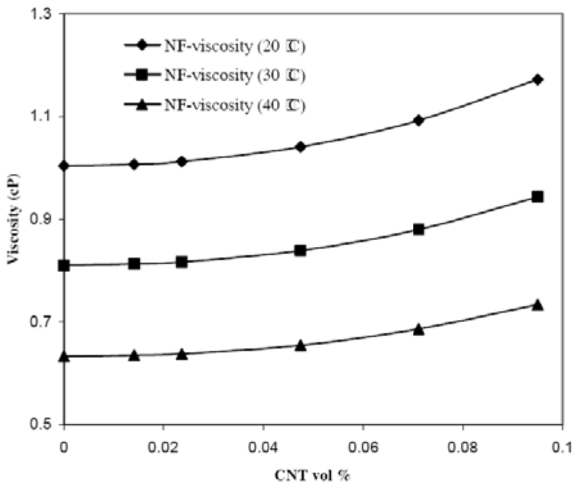



**Figure 4.** Measured Viscosity of nanofluids versus CNT *vol%* and temperature.

$$\rho_{nf} = \varphi \rho_p + (1-\varphi)\rho_f \quad (2)$$

$$C_{p,nf} = \varphi C_{p,p} + (1-\varphi) C_{p,f} \quad (3)$$

Where $C_{p,p}$ and $C_{p,f}$ are specific heat of nanoparticles and base fluid respectively.

## 4. Results and discussion

### 4-1. Heat transfer calculations

The energy supplied by heating element could be calculated as follows:

$$Q_1 = V \times I \quad (4)$$

In which V and I are recorded electrical Voltage and Ampere. Also, heat absorbed by the flowing liquid is defined as:

$$Q_2 = \dot{m} C_p (T_{out} - T_{in}) \quad (5)$$

Where $\dot{m}$ is mass flow rate of entering fluid while $T_{out}$ and $T_{in}$ are measuring temperatures of outlet and inlet fluid flows into test tube section of the experimental setup.

Experiments show that the heat loss from element to surrounding is negligible and the difference of $Q_1$ and $Q_2$ is less than 2%. The average of them was used in calculations as:

$$Q = (Q_1 + Q_2)/2 \quad (6)$$

Heat flux per unit area is defined as follows:

$$q'' = \frac{Q}{\pi d_o L} \quad (7)$$

Where $d_o$ and $L$ are outlet diameter and length of the test section respectively. Therefore the experimental heat transfer coefficient is calculated as:

$$h^{exp} = \frac{q''}{(\bar{T}_w - \bar{T}_f)} \quad , \quad Nu^{exp} = \frac{h^{exp} d_i}{k} \quad (8)$$

$\bar{T}_w$ is average value of 7 wall temperatures that are measured during experiments and $\bar{T}_f$ is average of $T_{out}$ and $T_{in}$. All physical properties of working fluid are taken in $\bar{T}_f$ .

### 4-2. Validation of heat transfer system results

Initially, experiments were done with water in plain tube to evaluate the accuracy of experimental system. The results are compared with ESDU (Engineering Science Data Unit) equation as follows:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{k_1 + k_2\left(\frac{f}{8}\right)^{0.5}\left(Pr^{2/3} - 1\right)}$$

$$4000 < Re < 5\times10^6 \; , \; 0.5 < Pr < 2000$$

$$k_1 = 1 + 13.6\, f \qquad k_2 = 11.7 + 1.8\, Pr^{-1/3}$$

$$f = (1.82 \, Log\, Re - 1.64)^{-2} \quad (9)$$

Where *f* is friction factor. Water is entered into the test section in different flow rates (Re =5000 - 20000) and all temperatures of water and tube wall are recorded in constant heat flux of 1500 W. Fig. 5 shows the results of heat transfer coefficient of water compared with ESDU equation. The average error of experimental heat transfer coefficient rather than ESDU equation is about 8% and from Fig. 5 it is observed that the results of heat transfer system are valid and it could be used for further experiments of nanofluids.

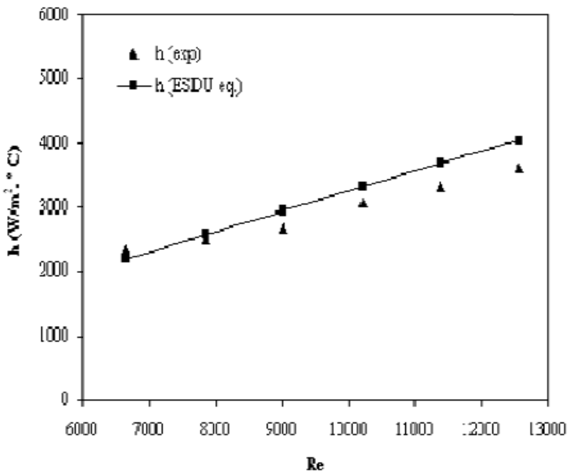
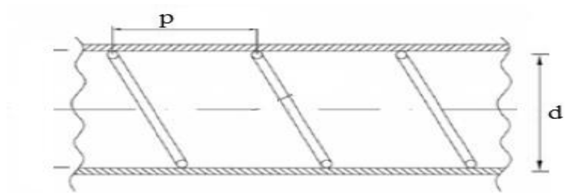



**Figure 5.** Validation of experimental heat transfer coefficient of water with the ESDU equation.

### 4-3. Experiments with water and wire coil inserts

To study the effect of wire coil inserts on heat transfer coefficient of water, a full-length wire coil with wire pitch of 2 ($p/d = 2$ in Fig. 6) is inserted into the test tube. Fig. 7 shows the enhancement of convective heat transfer coefficient with wire coil inserts. It is found from this Figure that augmentation of heat transfer decreases with increase of Reynolds number. It is observed from Fig. 7 and clearly from Fig. 8 that wire coil inserts could be useful in low Reynolds numbers and h-ratio is equal to unit in Re =20000. From Fig. 7 maximum enhancement of 102 % was observed in Re = 5700.




**Figuer 6.** Schematic diagram of wire coil inserts.

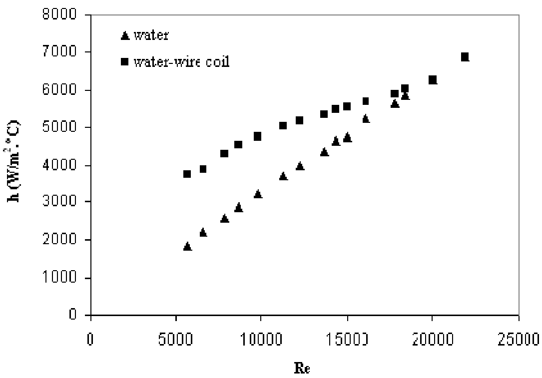



**Figure 7.** Enhancement of water heat transfer coefficient with wire coil inserts.

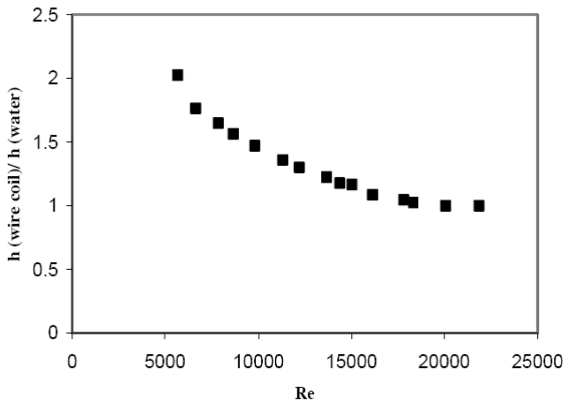



**Figure 8.** Heat transfer coefficient ratio of water-wire coil to water versus Re.

From nonlinear regression of obtained experimental data for water-wire coil insets in turbulent flow an empirical correlation was proposed as a function of Re and Pr with the average error of 2% as follows:

$$Nu = 1.795\, Re^{0.4028}\, Pr^{0.1394} \qquad (10)$$

Presented correlation could be used to predict Nusselt number in tube fitted with wire coil inserts in Re = 6000–13000.

**4-4. Experiments with nanofluids**

Three nanofluids with CNT concentration of 0.05, 0.1 and 0.2 *wt%* were used as working fluid and then convective heat transfer coefficient was determined experimentally in constant heat flux of 1500 W. Fig. 9 shows the comparison of experimental heat transfer coefficient of water and 3 weight concentration of nanofluids. It is found from Fig. 9 that convective heat transfer of water is enhanced by use of nanofluids. Also, the increase of CNT concentration increases heat transfer enhancement in the same Reynolds number. Heat transfer coefficient of nanofluids increases with Reynolds number in all CNT concentrations. With 0.1 *wt%* CNT- nanofluid maximum enhancement of 23% was achieved in Re = 16000.

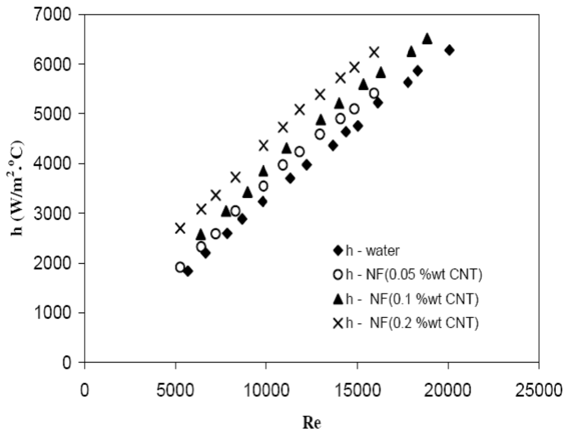



**Figure 9.** Comparison of experimental heat transfer coefficient of water and different nanofluids.

An empirical correlation was obtained from nonlinear regression of experimental results of 0.1 *wt%* nanofluid with the average error of 2.5 % as follows:

$$Nu = 0.0119\, Re^{0.8522}\, Pr^{0.4572} \qquad (11)$$

Proposed correlation is valid for 0.1 *wt%* CNT-water nanofluid in Re = 6000 – 19000.

**4-5. Experiments with nanofluid and wire coil inserts**

Wire coil was inserted in test section and two nanofluids of 0.1 and 0.2 *wt%* are forced to flow into test tube. The results of experimental heat transfer coefficient of the fluid in tube are shown in Fig. 10. It is observed from this Figure that convective heat transfer of nanofluids is enhanced in presence of wire coil inserts. Comparison of the results with water in the same Reynolds number and CNT concentration shows that heat transfer enhancement in combination with wire coil and nanofluids is more than nanofluid and wire coil individually. Wire coil inserts enhanced heat transfer of 0.1 *wt%* nanofluid by 72% in Re = 6400 and this enhancement for water is about 100%. Moreover, it is found from Fig. 10 that advantage of wire coil inserts is decreased in high Reynolds number.

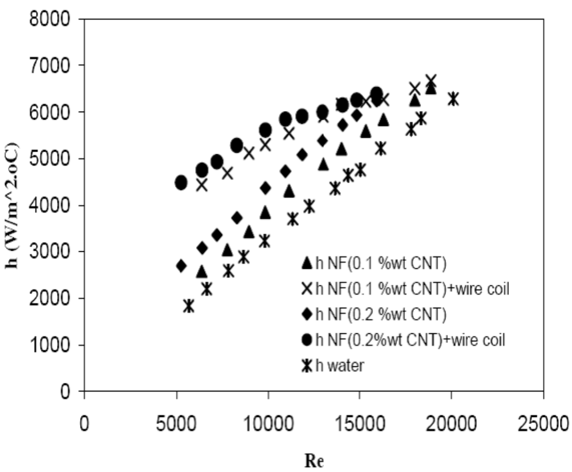



**Figure 10.** Comparison of experimental heat transfer coefficient of water, water-nanofluid, water-nanofluid-wire coil inserts.

For 0.1 *wt%* nanofluids in presence of wire coil another correlation could be presented from nonlinear regression of experimental data in Re = 6000–19000 as follows:

$$Nu = 1.591 Re^{0.3801} Pr^{0.2865} \quad (12)$$

**4-6. Pressure drop and friction factor of working fluid**

The friction factor of a fluid entering into the horizontal tube could be determined from the Darcy relation as:

$$f^{exp} = \frac{2}{\rho} \cdot \frac{D}{L} \cdot \frac{\Delta P^{exp}}{u^2} \quad (13)$$

Where *u* is average velocity that could be calculated from experimental volume flow rate and knowing the cross area of test tube. Parameters of *L*, *D* are length and inside diameter of the tube, respectively. $\Delta P$ is pressure drop of fluid and is experimentally evaluated by U-tube Mercury manometer as:

$$\Delta P^{exp} = (\gamma_{Hg} - \gamma_w) h_{Hg} = (13.55 - 1)\gamma_w h_{Hg}$$
$$= 12.55\gamma_w h_{Hg} \qquad , \gamma_w = \rho_w g \quad (14)$$

To validate the pressure drop system water is entered into test section in different flow rates and pressure drop measured using U-tube manometer. Fig. 11 shows the comparison of obtained results for experimental friction factor with Blasius equation for turbulent flow in smooth pipes as follows:

$$f = \frac{0.316}{Re^{0.25}} \quad (15)$$

As shown in this Figure the experimental results are in good agreement with theoretical relation of Blasius and pressure drop system is suitable for measuring friction factor of working fluids. The average observed error in this experiment was less than 6%.

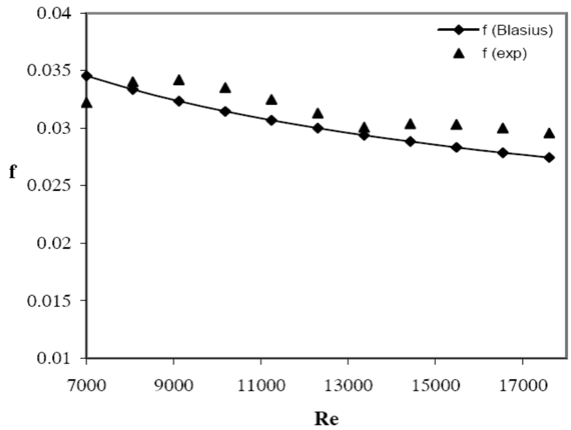



**Figure 11.** Comparison of experimental friction factor of water with Blasius equation.

Pressure drop of water in tube filled with wire coil experimentally measured and the results of friction factor calculation are compared with plain tube in Fig. 12. It is observed from this figure that pressure drop of water increase by 2.5-3 times when using wire coil inserts. This leads to an increase in the needed pumping power for the flowing working fluid.

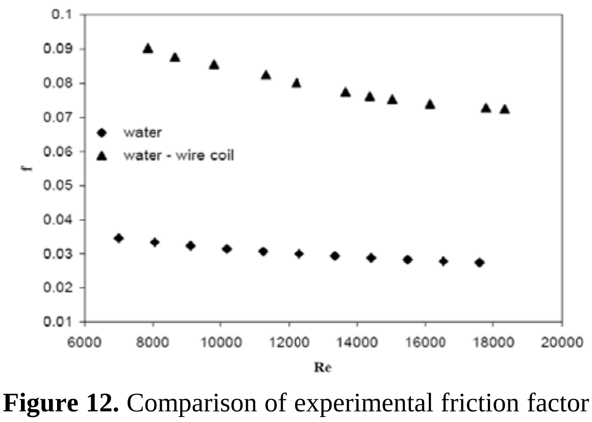



**Figure 12.** Comparison of experimental friction factor of wire coil inserts with water in plain tube.

Nonlinear regression of the results for water with wire coil inserts leads to a correlation with average error of 2% as follows:

$$f^{exp} = 0.9527\,Re^{-0.2626} \quad (16)$$

Presented correlation is effective to predict water friction factor in presence of wire coil in Re = 5000 – 20000.

The results of measured pressure drop of nanofluids in all cases have shown negligible increase in pressure drop of water. So the correlation for water–wire coil friction factor could be used to prediction of nanofluids–wire coil friction factor.

**4-7. Performance Evaluation**

To evaluate the advantages of the heat transfer system using enhanced tube, thermal performance was determined with proposed performance index (P.I) of Jafari Nasr *et al.* [22];

$$P.I = \left(\frac{1}{1 + R_{opp} \cdot h_t}\right)^{1.5} \sqrt{\frac{St^3}{f}} \quad (17)$$

Where $R_{opp}$ is opposing thermal resistance, $h_t$ is heat transfer coefficient of fluid in tube, $f$ is friction factor, and $St$ is Stanton number.

Performance index of tube enhanced by wire coil inserts and combination of 0.1 *wt%* nanofluids – wire coil inserts with $R_{opp}$ = 0.0001 are shown in Fig. 13. It is found from this figure that P.I decreases with increase of Reynolds number. Moreover, the tube filled with nanofluids–wire coil has higher performance than water–wire coil inserts in the same Reynolds number. Based on that analysis, the effect of opposing thermal resistance on P.I was studied. Decrease of P.I with increase of $R_{opp}$ was obtained from the results of Fig. 14.

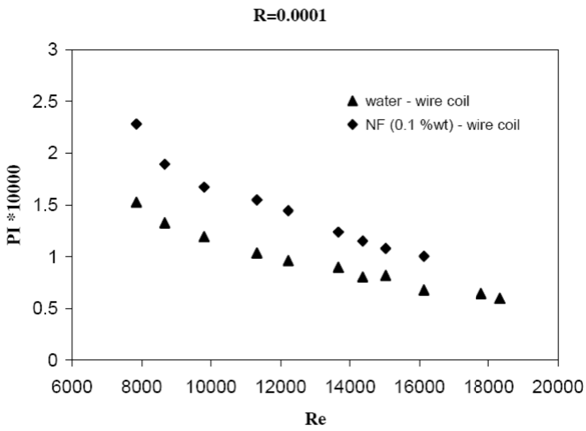



**Figure 13.** Comparison performance index of water-wire coil and NF-wire coil with $R_{opp}$=0.0001.

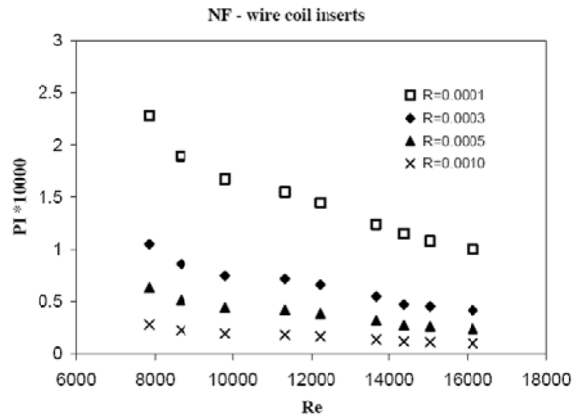



**Figure 14.** Performance index of NF-wire coil inserts with different Opposing thermal resistance.

## 5. Conclusions

High purity CNTs was produced by CVD process and functionalized by acid treatment. Aqueous nanofluids of these CNTs were prepared in five concentrations less than 0.1 *vol* % (0.2 wt%) and their thermal conductivity and viscosity were measured experimentally. The experiment's results show higher thermal conductivity enhancement in comparison with previous works done by researchers on CNT-water nanofluids and increase of nanofluids thermal conductivity with CNT *vol%* and temperature. In 25 °C with 0.1 *vol*% (0.2 wt%) CNT in water, maximum thermal conductivity enhancement of 25% was observed in experiments. Also, obtained results of viscosity experiments in 20 – 40 °C show that viscosity of nanofluids increase with CNT *vol%* and temperature reduction.

Turbulent convective heat transfer coefficient and pressure drop of water and nanofluids entering the plain tube and tube fitted with wire coil inserts were measured separately in constant heat flux of 1500 W for electrical element. To validate the experimental system, the result of Nusselt number of water was compared with ESDU equation and good agreement was achieved. Enhancement of convective heat transfer of water with wire coil inserts was observed from the experiment results. Heat transfer coefficient of water increases with Reynolds number but thermal enhancement by wire coil decreases in high Re.

Nanofluids with CNT concentration of 0.05, 0.1 and 0.2 *wt%* are entered into the test tube and enhancement of heat transfer with nanofluids was observed from experimental results. Also, heat transfer coefficient of nanofluids increases with Reynolds number and CNT concentration. With 0.1 *wt%* CNT-nanofluid maximum enhancement of 23% was achieved in Re = 16000. Nonlinear regression of experimental data leads to an empirical correlation for prediction of Nusselt number of 0.1 *wt%* CNT-water nanofluids. Using wire coil inserts in combination with nanofluids enhanced convective heat transfer more than wire coil and nanofluids alone, especially in low Re.

The results of measuring pressure drop were showed that presence of CNTs in water had negligible effect on friction factor of water. Also, wire coil inserts increase pressure drop by 2.5-3 times that of the increase needed for pumping power. Performance index of heat transfer system by using wire coil and combination of wire coil and nanofluid decreases with Re and performance of wire coil–nanofluid is higher than wire coil–water in the same Re. Also, performance index of enhanced tube decreases with increase of opposing thermal resistance.

## Acknowledgements

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