IMPACT OF COIL PITCH ON HEAT TRANSFER ENHANCEMENT OF A TURBULENT FLOW OF α-Al_2O_3-DISTILLED WATER NANOFLUID THROUGH HELICAL COILS

by

Mustafa S. ABDULLAH [a,b]* **and *Adnan M. HUSSEIN*** [a]

[a] Northern Technical University, Kirkuk, Iraq
[b] Erbil Polytechnic University, Erbil, Iraq

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The current study experimentally examines the impact of coil pitch on heat transfer behavior and friction factor through helical coils for α-Al_2O_3-distilled water nanofluid turbulent flow. These tests were conducted on coils with coil pitches of 20 mm, 35 mm, and 50 mm. The nanoparticle volume fraction was 0.1%. The nanoparticles in a 0.1% volume concentration of nanofluid increased the heat transfer rate and friction factor compared to those of distilled water. Increases in coil pitch also resulted in greater heat transfer efficiency. A correlation between the Reynolds number, the Prandtl number, and the curvature ratio of the coil was also shown to be connected to the Nusselt numbers for the flow of nanofluids within the coils.

Key words: *α-Al_2O_3-distilled water nanofluid, coil pitch, curvature ratio, Nusselt number, friction factor, Shell and helical coil*

Introduction

Heat transfer enhancement procedures are used to boost the efficiency of heat exchangers so that they can carry out a specific heat transfer task. They may classify these methods as either active or passive, but those are only broad categories. The active methods need the application of some kind of external force, such as an electric field, sound waves, or surface vibrations. Fluid additives or unique surface geometries are necessary for the passive approaches. One of the methods to enhance passive heat transfer involves the use of helical coils, which have been developed because they are constructed in a compact manner and have a high heat transfer coefficient [1].

The flow in helical coils is characterized by the formation of a secondary flow, which is caused by centrifugal force. This flow pattern is often characterized by the presence of two cells rotating in opposite directions, resulting in a symmetrical pattern. The conventional helical coil's overall geometry is determined by several factors, including the pitch, p, coil diameter, D, coil curve ratio, γ, and tube diameter, d [2].

Liu and Masliyah [3] have performed a numerical study of fully evolved flows in finite-pitch helical pipes. In the case of helical coils where there is a consistent wall temperature and heat flow along the wall, Manlapaz *et al.* [4] have presented correlations between friction factor and Nusselt number. The effects of the Dean number on friction factor and heat transfer were studied by Patankar *et al.* [5] Guo *et al.* [6] conducted a correlation of pipes coiled in a

* Corresponding author, e-mail: Mustafa.sabah@ntu.edu.iq

helical shape in both the transitional and mature regions. This correlation is exclusive to the configuration of the coils and does not consider other characteristics (*e.g.* curvature ratio, γ).

However, the heat transfer rate in heat exchangers can be increased by the medium of its heat execution, so selecting the proper fluid is essential. Studies of nanofluids have shown that the presence of nanoparticles modifies the fluid's properties. This is due to the thermal conductivity of nanofluids being improved in comparison base fluids [7]. Mixing solid nanoparticles with a liquid base results in nanofluids. Many studies have investigated the production, characteristics, and potential uses of nanofluids [8-14].

Significant progress has been made in the field by Li and Yuan [15], who have developed the initial numerical correlation for determining the Nusselt number in nanofluids containing Al_2O_3 and water. Results showed that the nanofluid provides a statistically significant increase in heat transfer coefficient over the basic fluid at a constant Reynolds number. Rakhsha *et al.* [16] have performed experiments with a Cuo-water nanofluid in a tube using turbulent forced convection. The friction factor coefficient and Nusselt number are modeled using correlations. They found that the pressure drop and the heat transfer coefficient increase when the curvature ratio and Reynolds number increase. Hojjat *et al.* [17] observed the frictional pressure drops of non-Newtonian nanofluids in a circular tube and concluded that the base fluid's pressure drop pattern applies to nanofluids under laminar and turbulent flow conditions, as determined by the Reynolds nimber. Using a laminar flow by combining the geometry effect utilizing nanofluids inflow in coils, Sasmito *et al.* [18] studied the enhancement of passive heat transfer in coiled square tubes using nanofluids consisting of Al_2O_3-water and CuO-water. Their findings that adding nanoparticles, even in concentrations as low as 1%, boost heat transfer efficiency. They emphasized that, based on the performance index, using Al_2O_3 nanoparticles is more beneficial than using CuO nanoparticles at an equal volume fraction.

Jamshidi *et al.* [19] found that adding nanoparticles to a two-phase closed heat exchanger greatly enhanced its heat transmission characteristics. In addition, Algarni *et al.* [20] report a 13% and 17% enhancement in the average heat transmission when using Al_2O_3-water nanofluid rather than with plain water. Also, they mentioned that increasing the tube diameter and lowering the coil diameter boosts model efficiency.

In order to improve the turbulent flow of TiO_2 nanofluid inside double-pipe heat exchangers with helical coil inserts, Ebrahimi-Moghadam *et al.* [21] performed an extensive thermohydraulic analysis. Their comparison findings indicated that the use of nanoparticle volume fraction resulted in superior thermal performance when combined with the pitch-to-diameter ratio of helical coil inserts. Similarly, Sundar *et al.* [22] conducted experiments to study turbulent convective heat transfer and friction factor characteristics of Fe_3O_4 nanofluid with and without twisted tape inserts flowing through a uniformly heated horizontal circular tube. Their experimental results showed that both the friction factor and heat transmission could be improved by using a coiled tape insert with a 1.231 twist ratio compared to flowing water in a conventional pipe at the identical Feynolds number. The impact of $A1_2O_3$ on similar experiments was also examined, and it was found that as the volume concentration of nanofluid increases, the heat transfer coefficients also increase, but they decrease as the aspect ratio decreases [23].

In a horizontally curved tube, Akbarnia and Behzadmehr [24] used numerical methods to examine the Al_2O_3-water nanofluid laminar convection. The authors found that the skin friction coefficient was not significantly affected by the volume percentage of the nanoparticle. Huminic and Huminic [25] demonstrated that the use of 2% CuO nanofluid in water can improve the heat transfer rate in double-tube helix heat exchangers by up to 14% compared to using only water.

The temperature efficiency of nanofluid in helical coils is largely determined by the coil width and coil pitch, as pointed out by Kahani *et al.* [2]. Mola *et al.* [26] conducted experiments with a $CuFe_2O_4$-water nanofluid for heat transfer, where they found that increasing the coil pitch-to-tube diameter ratio or reducing the curvature ratio resulted in improved heat transfer rates for the base fluid. Sisodiya and Geete [27] argued that using nanofluids in a helical tube is more effective in increasing the convective heat transfer coefficient as compared to using pure liquids. Finally, Kumar *et al.* [28] reported a 55% increase in Nusselt number and a 26% increase in friction factor for turbulent flow of Al_2O_3-water nanofluid in helically coiled tubes. However, they did not take into account the effect of coil geometry in their experiments.

In this investigation, an α-Al_2O_3-distilled water (DW) nanofluid was used to investigate the impact of the coil curve ratio and the pitch of the coils on the turbulent heat transfer and friction factor in helically coiled tubes. Also, a comparison between nanofluid and pure water was experimentally involved in this research.

Experimental methodology

Nanofluid preparation

In a study of heat exchange in a helical coil tube, nanoparticles of +99.9% pure α-Al_2O_3 measuring 50 nm in size were used. Figure 1 shows SEM images of α-Al_2O_3 nanoparticles indicating their morphology characteristics. In this research, the perfect amount of mixing and sonication was used to keep the nanoparticles evenly dispersed throughout the base fluid. The α-Al_2O_3-DW nanofluid is made with a volume concentration of 0.1 vol.%. The weight of α-Al_2O_3 nanoparticle is measured using an analytical balance to achieve the desired volume concentration. To ensure the nanofluids are uniform and stable, they are stirred with a SNIJDERS Model 34521 magnetic stirrer and then subjected to an ultrasonic homogenizer, the VEVOR ultrasonic Model 328-158293, for 1 hour. In this investigation, nanoparticle sedimentation was observed following ultra-sonication. The nanofluid was continuously monitored up until the particle separation phase began to determine how long the nanoparticles would remain stable in the water and how long it would take for them to disperse uniformly throughout the water. At a volumetric ratio of 0.1%, it has been observed that the stability of a nanofluid is maintained for about 72 hours. Figure 2 shows a photograph of the process of monitoring the nanofluid sample. In tab. 1 the thermo-physical properties of water and α-Al_2O_3 are presented.

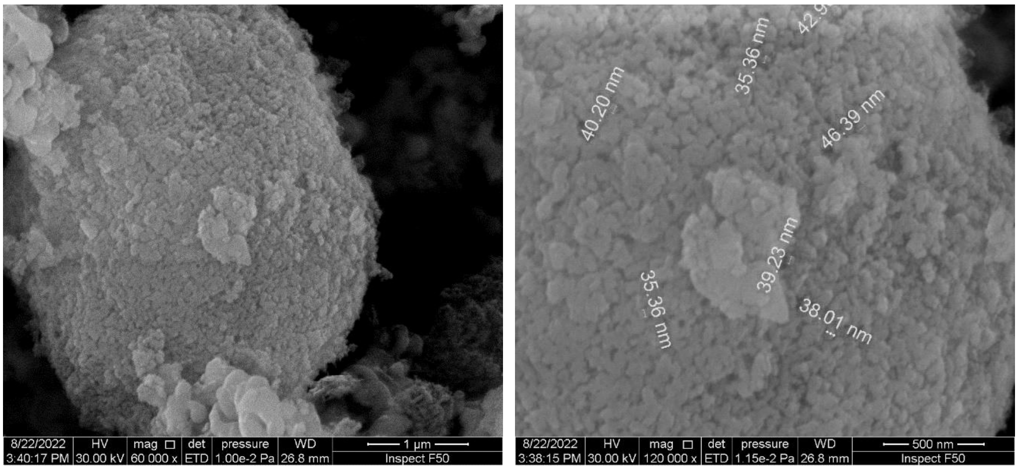

Figure 1. The SEM images of α-Al_2O_3

Table 1. Thermo-physical properties of water and α-Al_2O_3 [29]

Fluid	Density, [kgm^{-3}]	Specific heat, [Jkg^{-1}K^{-1}]	Thermal conductivity, [Wm^{-1}K^{-1}]
Water	995.1	4182.8	0.603
α-Al_2O_3	3970	765	40

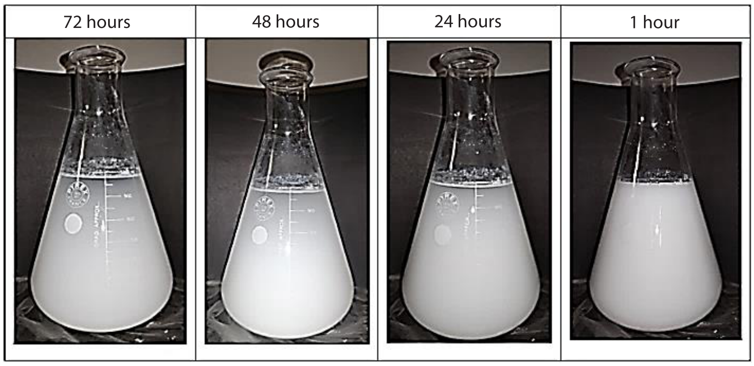

Figure 2. Time-lapse photograph of α-Al_2O_3 sample stability

Test rig set-up and procedure

The experimental apparatus comprises a tank (15 liters), a pump, a heat transfer test sections, a pressure gauge, and a flow rate measuring device, as illustrated in fig. 3. The test sections made use of three copper helical coils. To make the coil, a straight tube was initially filled with salt to keep its circular cross-section as undistorted as possible throughout the manufacturing process. Special mandrels were used for the winding process. Table 2 displays the physical parameters of the helical coils.

The *K*-type thermocouples were installed at the inlet and outlet of both the coil and the shell in the test rig, and three thermocouples were placed in the middle of the coil for each test section measure the bulk temperatures of the working fluids. The accuracy of all thermocouples used was 0.25% of the full scale.

To reduce the amount of heat lost to the surrounding environment, fiberglass layers that were 3 cm thick were used to insulate all heat transfer sections.

Also, a pressure gauge was utilized to determine the amount of pressure loss experienced by the test rig. A pump was utilized to circulate the working fluid from the storage tank throughout the system. The nanofluid tank was then topped up and the pump was turned on. It was at this point that electric resistance was activated, and the water's temperature began to rise. In the beginning, Both parallel flow and counter flow were examined, and it was observed that counter-flow produced more satisfactory results than parallel flow. After that,It has been determined from preliminary experiments that the system requires 15-20 minutes to attain a steady-state before measurements can be obtained. At least two separate measurements were taken for each variable to ensure precision. Flowrate, bulk mean temperatures (at the inlet and outlet), wall temperatures (at the surface of the coil), and pressure drops on the coil side were all monitored.

Data analysis

The following equations were used to determine the experimental convective heat transfer coefficient and the fluid's Nusselt number [30]:

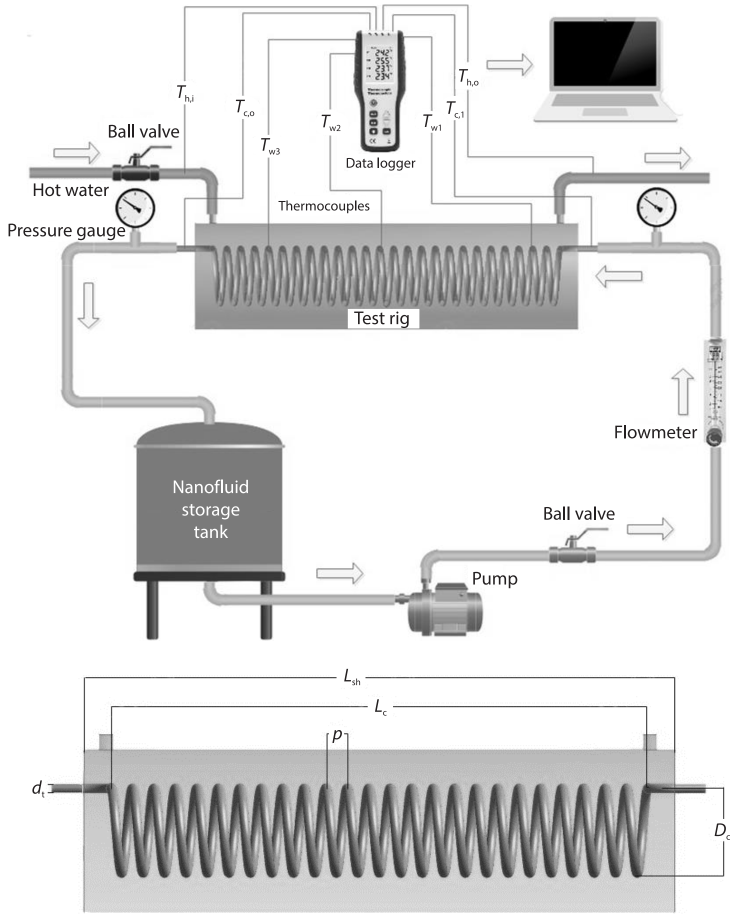

Figure 3. Illustration diagram of the test rig with the physical parameters of the helical coil

$$h_i = \frac{q_{\text{avg}}}{A_i\left(T_w - T_{c,\text{avg}}\right)} \tag{1}$$

$$\text{Nu}_\text{c} = \frac{h_\text{i} d_\text{i}}{k_\text{i}} \tag{2}$$

where T_w and $T_{c,\text{avg}}$ are the wall temperature and average coil temperature, respectively.

Table 2. Physical parameters of the helical coils

Coil	d_t [mm]	t [mm]	L_c [mm]	D_c [mm]	γ	p [mm]	N
Coil-1	8.5	0.5	6224	152.4	0.08	20	25
Coil-2			3417		0.14	35	14.28
Coil-3			2390		0.2	50	10

Additionally, Wu *et al.* [31] and Rogers and Mayhew [32] have presented the following correlations for estimating the Nusselt number in turbulent flow through a helical coil:

$$\mathrm{Nu} = 0.089\,\mathrm{De}^{0.775}\mathrm{Pr}^{0.4} \tag{3}$$

$$\mathrm{Nu} = 0.023\,\mathrm{Re}^{0.85}\mathrm{Pr}^{0.4}\left(\frac{d}{D}\right)^{0.1} \tag{4}$$

where De, Re, and Pr are the Dean, Reynolds, and Prandtl numbers, respectively, which can be expressed:

$$\mathrm{De} = \mathrm{Re}_\mathrm{i}\sqrt{\frac{d_\mathrm{i}}{D_\mathrm{c}}} \tag{5}$$

$$\mathrm{Re} = \frac{\rho v d}{\mu} \tag{6}$$

$$\mathrm{Pr} = \frac{\mu c_p}{k} \tag{7}$$

In addition, a differential pressure gauge is used to measure the pressure drop in the inner coil tube and can be obtained [33]:

$$\Delta P = P_\mathrm{in} - P_\mathrm{out} \tag{8}$$

In order to estimate the friction factor of a coiled tube, the following correlations can be used [34]:

$$f = \frac{\Delta P}{\left(\dfrac{L}{d_\mathrm{i}}\right)\left(\dfrac{\rho u_\mathrm{i}^2}{2}\right)} \tag{9}$$

In this study, the α-Al_2O_3-DW nanofluid was used. The physical properties (density, heat capacity, viscosity, and thermal conductivity) of the α-Al_2O_3-DW nanofluids are defined [2]:

$$\rho_\mathrm{nf} = (1-\varphi)\rho_\mathrm{w} + \varphi\rho_\mathrm{np} \tag{10}$$

$$c_{p_\mathrm{nf}} = \frac{(1-\varphi)(c_p)_\mathrm{w} + \varphi(\rho c_p)_\mathrm{np}}{(1-\varphi)\rho_\mathrm{w} + \varphi\rho_\mathrm{np}} \tag{11}$$

$$k_\mathrm{nf} = \frac{k_\mathrm{np} + 2k_\mathrm{w} + 2(k_\mathrm{np} - k_\mathrm{w})\varphi}{k_\mathrm{np} + 2k_\mathrm{w} - (k_\mathrm{np} - k_\mathrm{w})\varphi}k_\mathrm{w} \tag{12}$$

$$\mu_\mathrm{nf} = (1 + 2.5\varphi)\mu_\mathrm{w} \tag{13}$$

Results and discussion

Validation of Nusselt number

The DW was employed to verify the precision and dependability of experimental measurements before systematically conducting experiments on nanofluids. The theoretical eqs. (3) and (4) for turbulent flow were used to compare the experimental data. Figure 4 displays the comparison between the theoretical predictions and experimental results of the Nusselt number for the helical coils. Figure 4 depicts that at Reynolds numbers ranging from 10280-32249 and 0.1% volume concentrations of α-Al_2O_3 nanoparticles. The deviation of the experimental data from the numerical predictions for the helical coils was +6.9% and –26%.

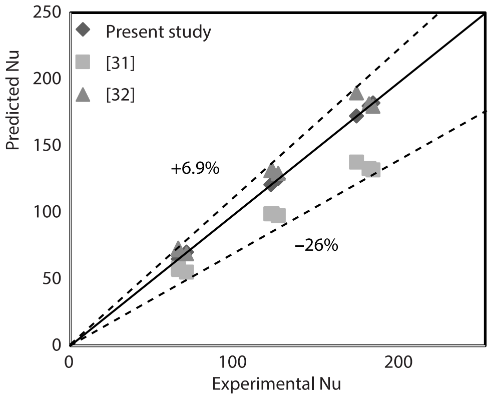

Figure 4. Experimental and predicted Nusselt numbers of coils-side for α-Al_2O_3-DW

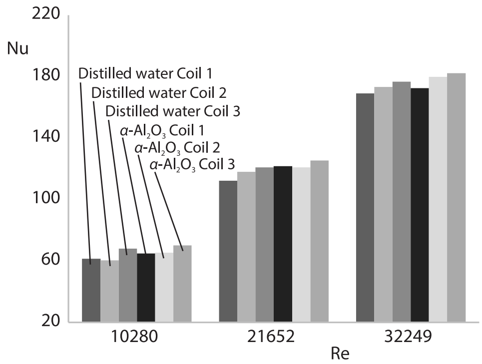

Figure 5. Pitch effect on heat transfer at Reynolds number

Effect of coil pitch on heat transfer

Figure 5 Shows the relationship between the Reynolds number and the volume concentration of the nanofluid, as well as the Nusselt number for the flow within Coil 1 (p = 25 mm), Coil 2 (p = 35 mm), and Coil 3 (p = 50 mm). As can be seen in fig. 5, the flow within the coil with the largest pitch spacing (Coil 3) exhibits a larger Nusselt number, which indicates a better heat transfer rate, although this is most apparent at higher Reynolds number. For instance, for a constant Re = 32249, the Nusselt number for a 0.1% volume concentration of nanofluid within Coils 1, 2, and 3 are (172.42, 179.90, and 182.22), respectively, but at Re = 10280, the improvement for Nusselt number is just (64.89, 65.19, and 70), respectively. Buoyancy, which only has an effect on the flow structure at very high nfreynolds number, is to blame for this pattern (where the centrifugal forces are big). Pitch also affects the centrifugal force on a fluid in motion. As a result, secondary flows in the pipe's cross-section will be impacted.

Effect of coil pitch on fraction factor

In contrast to the Nusselt number, the friction factor decreases as the Reynolds number of the coil side increases. Figure 6 shows that when the Reynolds number of the coil side is increased from 10280-32249 while maintaining a constant coil pitch (p = 50 mm), the friction factor decreases in Coil 3 from 0.044587-0.035232. This can be attributed to the fact that as the Reynolds number increases, the flow rate and velocity also increase, leading to a decrease in the friction factor, which is inversely proportional to the flow rate.

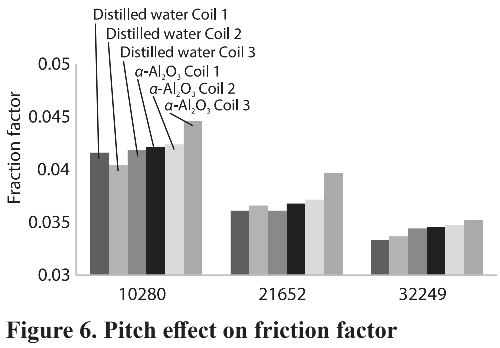

Figure 6. Pitch effect on friction factor at Reynolds number

Correlation for prediction of Nusselt number

The following correlation can be used to estimate the Nusselt number of nanofluid-flow inside helical coils by using the least square method of experimental data points and

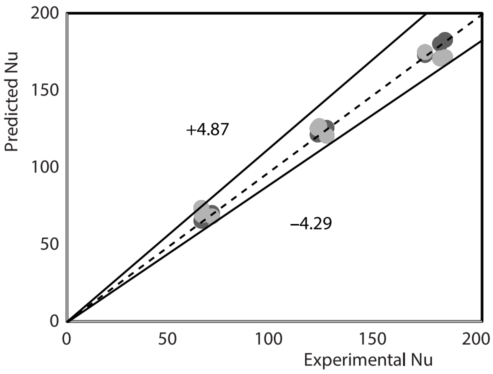

Figure 7. Comparison of the experimental and predicted Nusselt numbers for the 1, 2, and 3 coil sides

can be used to make accurate predictions. After correction, the value of the correlation coefficient is $R^2 = 99.46\%$:

$$\mathrm{Nu_c} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4}\gamma^{-0.08} \tag{14}$$

The parameters' ranges are $10280 \le \mathrm{Re} \le 32250$, $2.88 \le \mathrm{Pr} \le 3.33$, and $0.88 \le \gamma \le 0.20$. The predicted Nusselt number, as seen in fig. 7, are within +4.87% and –4.29% of the experimental results values.

Conclusions

The present research investigated the friction factor and heat transfer rate of α-Al_2O_3-DW nanofluid-flow through helical coils with varying geometries. The experiments were conducted under constant heat flux boundary conditions for the turbulent flow regime. The main outcome of the study can be condensed, are as follows.

- Coil-side Nusselt numbers in counter-flow configurations were found to be higher than those in parallel-flow configurations.
- Heat transfer coefficients on the coil side were found to be greater for larger pitch coils compared to smaller pitch coils.
- By utilizing a nanofluid instead of water in an exchanger, both the overall heat transfer coefficient and the heat transfer coefficient increase. Furthermore, as the flow rate of the nanofluid increases, these coefficients continue to increase.
- The maximum heat transfer coefficient was recorded on the Coil 3 with a pitch of 50 mm and a flow rate of 6 Lpm, which was 13470.97 W/m^2°C. This value showed an improvement rate of 7.45% compared to the basic fluid.
- The maximum Nusselt number was recorded at a flow rate of 6 Lpm for a nanofluid with a volume concentration of 0.1% at the Coil 3 with a pitch of 50 mm, which was 182.22. The improvement rate compared to the water-based liquid was 7.72%.
- As the flow rate decreased, the friction factor inside a helically coiled tube increased, with the maximum value being 0.044587 at the Coil 3 with a pitch of 50 mm and a flow rate of 2 Lpm. While the lowest value was 0.03333 at Coil 1 with a pitch of 20 mm at the same flow rate conditions.

Nomenclature

A – coil surface area, [m^2]
c_p – specific heat, [Jkg^{-1}K^{-1}]
D – coil diameter, [m]
d – tube diameter, [m]
De – Dean number, [–]
k – thermal conductivity, [–]
L – coil length, [m]
N – number of turn
Nu – Nusselt Number, [–]
p – pitch, [m]
Pr – Prandtl number, [–]
q – heat flux
Re – Reynolds number, [–]
T_h – temperature, [°C]
v – velocity, [ms^{-1}]

Greek symbols

α – alpha
γ – curve ratio, ($\gamma = D/d$)
μ – the viscosity of the fluid, [Pa·s]
ρ – density of nanofluid, [kgm^{-3}]
φ – particle concentration

Subscripts

avg – average
c – coil
i – inside
nf – nanofluid
np – nanoparticle
w – wall or water

Acronyms

$CuFe_2O_4$ – copper iron oxide
CuO – copper(II) oxide
DW – distilled water
Fe_3O_4 – iron (III) oxide
SEM – scanning electron microscopy

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