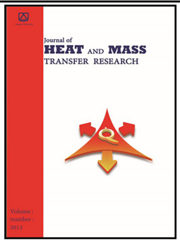
Journal of Heat and Mass Transfer Research 2 (2015) 45-50

Semnan University

Journal of Heat and Mass Transfer Research

Journal homepage: http://jhmtr.journals.semnan.ac.ir



Analysis of variance of nanofluid heat transfer data for forced convection in horizontal spirally coiled tubes

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PAPER INFO

History:

Received 22 April 2014
Received in revised form 5 July 2015
Accepted 27 August 2015

Keywords:
Nanofluids
Spiral coil
ANOVA
Nu number
Thermal conductivity

ABSTRACT

In the present study, an experimental study is carried out to investigate the effect of adding Al and Cu nanoparticles to the base fluid (water) on the heat transfer rate in a spirally coiled tube. The spirally coiled tube is fabricated from the straight copper tube with the inner and outer coil diameters of 100 and 420 mm, respectively. The experiments have been done for water and two types of nanofluids with different concentrations and at various operational conditions. The Thermal conductivities of these fluids have been measured experimentally. The results show that thermal conductivity of Cu-water nanofluid is about 18 % more than Al-water nanofluid at 2.23 vol. %. The forced convective heat transfer has been studied by changing the wall temperature, concentration, *Gz* number, and nanofluid type. The Results indicate that nanofluids have significant positive effect on convective heat transfer coefficient. Also, the Nusselt number increases with an increase in the *Gz* number. The most important effective parameters on the heat transfer are found to be the *Gz* number based on the analysis of variance (ANOVA) method. Based on the statistical analysis, a new correlation for the Nusselt number is introduced.

1. Introduction

Due to enhanced heat transfer characteristics, the curved tubes have been extensively used in industrial applications such as refrigeration, geothermal heating/cooling, air conditioning, etc. According to these wide ranges of curved tube applications, the heat transfer enhancement has been emphasized by many researchers [1-6].They tried to find new ways to enhance the heat transfer rate and thermal performance of the curved tubes and especially the spirally coiled tubes. One of the newest methods to increase the heat transfer rate is to use the nanofluids [7]. Mirzaei and Dehghan [7] showed that adding of only few vol. % of nanoparticles has the potential to increase the heat transfer rate up to 20%. They showed that this enhancement in the thermal performance of microchannels is more evident by the temperature-dependent property approach. Jamal-Abad et al. [8] extensively analyzed the use of nanoparticles added to the working fluid (water) to increase the heat transfer rate and thermal performance of a spirally coiled tube. Jamal-Abad et al. [9] recently interpreted experimental measurements of the shear rate response versus time for some nanofluids based on the non-Newtonian model of Power-Law. They showed that the best model to express the shear rate vs. time response of nanofluids is the non-Newtonian model. In addition, they found that adding of few vol.% of nanoparticles may decrease the kinematic viscosity of the working fluid which is durable in decreasing the pressure drop through heat exchangers.

The aim of the present experimental investigation is to study of heat transfer rate of

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nanofluids in spirally coiled tubes. In this study, nanofluids consisting of Aluminium and Copper nanoparticles were prepared in water. The forced convective heat transfer inside a spirally coiled tube was investigated at different concentrations of nanoparticles and operating temperatures in the laminar flow regime. The Nanofluids were used as the working fluid under the constant wall temperature boundary condition. The experimental results for the two types of nanofluids were analyzed based on the analysis of variance (ANOVA) method.

2. Experimental procedure

The schematic diagram of the experimental set-up is shown in Fig. 1. The Relevant dimensions of the spirally coiled tube and thermo-physical properties of Al and Cu nanoparticles are given in Tables 1 and 2. Details of the set-up were introduced in Ref. [8] and consequently, any duplicate information offering is avoided.

3. Nanofluid preparation

To protect nanoparticles from oxidation, the nanofluids were prepared by the one-step method using Al and Cu nanoparticles. For more information regarding to the advantages and disadvantages of one and two-step methods, one can refer to Refs. [8, 10].

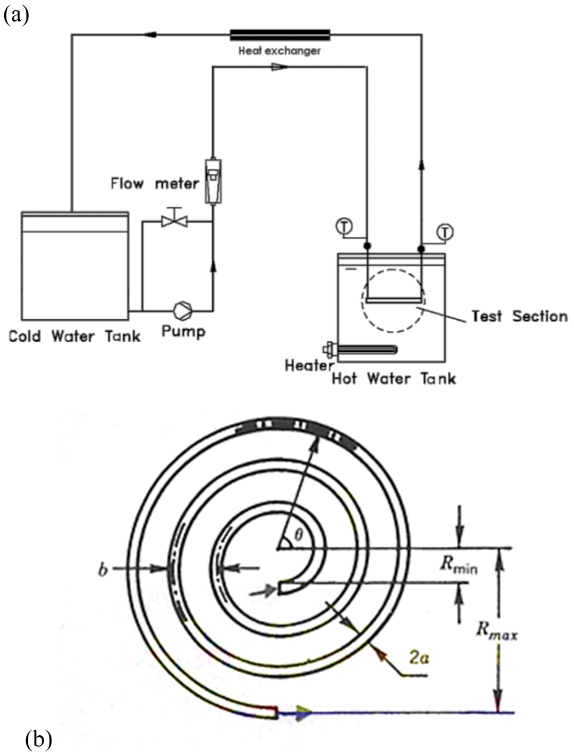

Figure 1 (a) Schematic of the experimental setup, (b) schematic diagram of the spirally coiled tube.

Table 1 Dimensions of the spiral coil

Outer diameter of tube	9 (mm)
Space between tube	30 (mm)
Outer spiral-coil tube diameter	420 (mm)
Inner spiral-coil tube diameter	100 (mm)
Average radius	130 (mm)
Length of spiral-coil tube	5000 (mm)
Curvature ratio	0.034

Table 2 Physical properties of nanoparticles

Density (g/cm^3)	mean diameters (nm)	thermal conductivity (W/m.k)	Particle
8.954	30-40	401	Cu
2.707	20-30	237	Al

4. Data processing

The heat transfer characteristics of fluids are defined in terms of the convective heat transfer coefficient and the Nusselt number [11]:

$$\bar{h}_L = -\frac{\dot{m}C_p}{pL} ln \frac{T_s - T_{m,o}}{T_s - T_{m,i}} \tag{1}$$

$$\overline{Nu} = -\frac{1}{\pi} Gzln \frac{T_s - T_{m,o}}{T_s - T_{m,i}} \tag{2}$$

where

$$\mathrm{Gz} = \frac{\dot{m}C_p}{kL} = \frac{\pi}{4}\frac{D}{L} RePr \tag{3}$$

where $\dot{m}$ is the mass flow rate of the fluid, k is the fluid thermal conductivity, C_p is the effective specific heat of the fluid and L represented tube length.T_s, $T_{m,o}$ and $T_{m,i}$ are the averaged wall temperature, the outlet and inlet temperatures of the fluid, respectively.

The thermophysical properties of nanofluid were calculated at the bulk temperature of the nanofluid by the following equations [12, 13]:

$$\rho_{nf} = \phi\rho_s + (1-\phi)\rho_b \tag{4}$$

$$\mu_{nf} = \mu_w(1 + 2.5)\phi \tag{5}$$

$$C_{p,nf} = \frac{\phi(\rho_s C_{ps}) + (1-\phi)(\rho_b C_{pb})}{\rho_{nf}} \tag{6}$$

Where $C_{p,nf}$ is the specific heat of the nanofluid, ϕ is the volume concentration, μ_{nf} is the viscosity of the nanofluid and ρ_{nf} is the effective density of nanofluid. The Subscripts b, s, and nf refer respectively to the base fluid, the nanoparticles, and the nanofluid. The properties of the nanofluid shown in the above equations are evaluated from water and nanoparticles at the bulk temperature.

5. Results and discussion

5.1 Validation

To evaluate the accuracy of the measurements, experimental system was tested with distilled water before measuring the convective heat transfer of nanofluids. The results were compared with the predictions of the following Kubair and Kuloor equation for laminar flows under the constant wall temperature boundary condition [14]:

$$Nu_T = \left(1.98 + 1.8\frac{a}{R_{avg}}\right) Gz^{0.7} \tag{7}$$

where a is the diameter of tube and R_{avg} represents the average radius. The experimental setup was validated by comparing the theoretical and experimental results of pure water. As shown in Fig. 2, a good agreement exists between the experimental data and theoretical results.

5.2 The thermal conductivity of nanofluids

Figure 3 indicates the thermal conductivity enhancement of Al-water and Cu- water nanofluids. The Results show that nanofluids have noticeably higher thermal conductivities than the pure base-fluid. For example, the thermal conductivity enhancement rises from a low amounts of 1.12 at 0.55 vol. % to a peak of 1.26 at 2.23 vol. %at 45 ^{0}C for the Cu-water nanofluid. With increasing temperature, the viscosity of the base fluid is decreased and the Brownian motion of nanoparticles is increased and consequently, the thermal conductivity increases. The slope of the thermal conductivity versus the volume fraction can be divided into two linear regimes. At lower concentrations, the slope was greater than mentioned higher concentrations. The Linear trend which is observed in this work has also been observed in the literature [15-18].

Figure 4 illustrates comparison between thermal conductivity of nanofluid ratio to the base fluid for different concentrations at 45 °C. Cu-water nanofluids have more enhancements in the effective thermal conductivity than those of Al-water nanofluids. For example, at the 0.55 and 1.12 vol.%, the effective thermal conductivity of Cu-water nanofluid increases respectively 12% and 26% whereas, the thermal conductivity of Al-water nanofluid increases respectively about 11% and 22%.

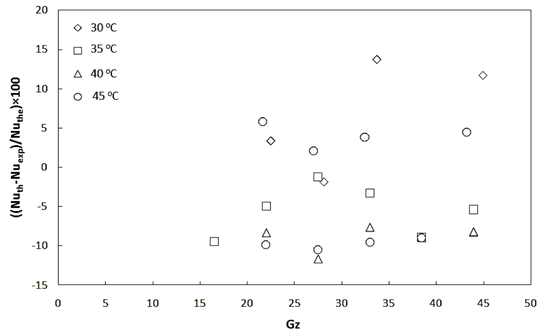

Fig. 2) Comparison between Kubair and Kuloor equation and experimental data for the Nusselt number of pure water

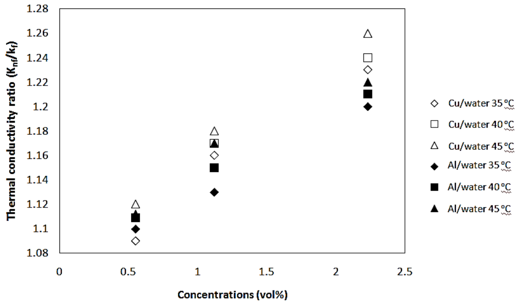

Figure 3 The Thermal conductivity ratios of Al-water nanofluids and Cu-water nanofluids

5.3 Convective heat transfer of nanofluid

Figure 5 demonstrates the Nu number for nanofluids versus Gz number for different concentrations at wall temperature 30 ^{o}C. It can be clearly seen that Nu enhances for both type of the nanofluids with a higher enhancement for the Cu-water nanofluid compared to the Al-water nanofluid at 2.23%.In a flow through a spiral coil, the centrifugal force strongly influences the Nu number. The Flow through a spiral, where in the radius of curvature varies continuously, results in a continuously variable centrifugal force .So, an increase in the Nusselt number can be seen for spirally coiled tubes. The secondary flow causes these oscillations by exposing the tube wall alternatively to the hot and cold fluids. There are similar results for 35 and 40 ^{o}C which can be seen in figures 6 and 7. For example, at wall temperature 35 ^{o}C and at the Gz number of about 28, the Nu number rises from 23 for Al-water with 2.23 vol. % to 27 for Cu-water at the same concentration. This trend can be seen for other concentrations in this situation.

The Nu number ratio (Nu_{nf}/Nu_f) for a specific concentration (0.55 vol %.) is illustrated in Figure 8. As expected, the Nusselt ratio increases with increasing the Gz number. This is due to the Nusselt number depends directly on the rat of mass

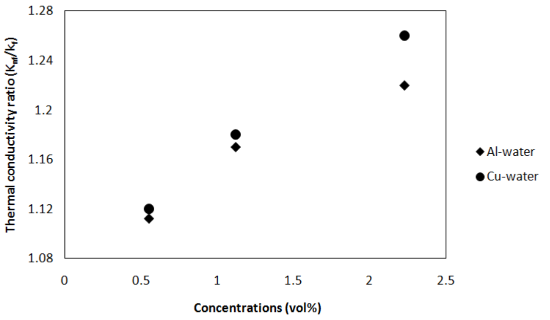

Figure 4 Thermal conductivity comparisons between Al-water and Cu-water nanofluid at 45 °C

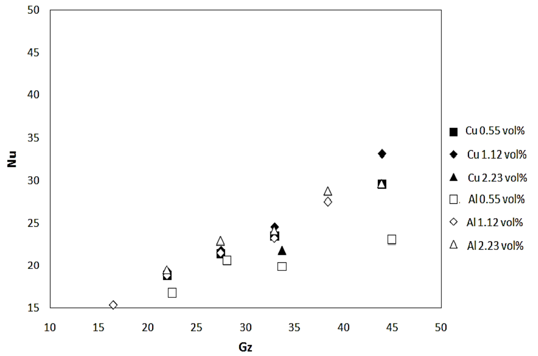

Figure 5 The Nusselt number of Al-water nanofluid in comparison with Cu-water nanofluid for different concentrations in wall temperature 30 °C

flow. In fact, there are significant fluctuations for the Nusselt number and there is no exact increasing trend when temperature rises because of the centrifugal force has a significant effect on the secondary flow. This secondary flow has significant effect on the fluid flow mixing, so it numerous fluctuations in the Nusselt number. These fluctuations once again reflect the effects of the secondary flow on the Nusselt number for both nanofluids at different temperatures. Also, the Nusselt number ratios of Al-water nanofluid are only slightly lower than mentioned Cu-water nanofluids. The Nu number of the Al-water nanofluid at 30, 35 and 40°C are about 10%, 6%, and 2% higher than those of pure water. The enhancement of the Nu number for Cu-water nanofluid at 30 °C exceeds 15%, while for 35 and 40°C are 6% and 5% respectively. This shows that, as the temperature increases, the Nu_f increases more than Nu_{nf}. Figures 9 and 10 illustrate this fact for Al-water nanofluid and Cu-water nanofluid at 1.12 and 2.23 vol. %, respectively.

5.4 Analysis of variance

Among the controllable factors, nanofluid type (A), concentration (B), temperature (C) and Gz number (D) were selected because they can affect the Nu number. The Variable factor levels are shown in tables 3.

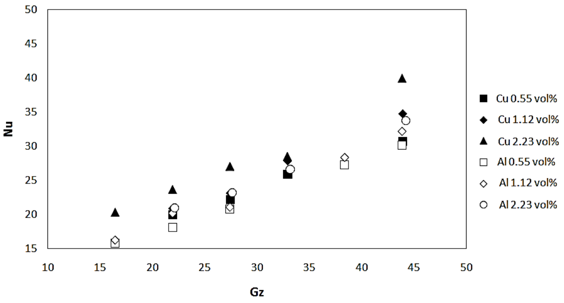

Figure 6 The Nusselt number of Al-water nanofluid in comparison with Cu-water nanofluid for different concentrations in wall temperature 35°C

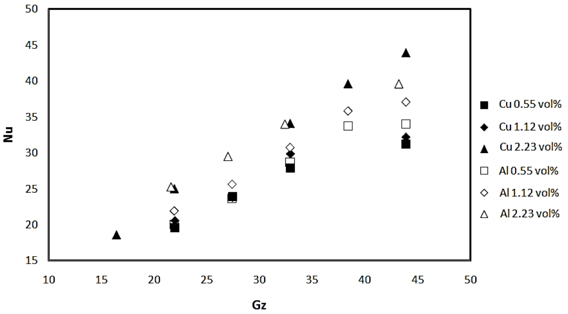

Figure 7 The Nusselt number of Al-water nanofluid in comparison with Cu-water nanofluid for different concentrations in wall temperature 40°C

The residual plot of Nusselt number is shown figure 11distributed evenly around the zero-line without showing any evident pattern. This satisfies the constant variance assumption. If the data are not evenly distributed around the mean, an extra term should be added to the model.

To reiterate the interpretation of ANOVA results, a calculated F-value that is greater than F_{crit} for a stated level of confidence (typically 90%) means that the difference being tested is statistically significant at that level. As an alternative to using the F-values, the p-value can be used to indicate the degree of confidence we have that there is a significant difference between means.

The aim of the analysis of variance (ANOVA) is to determine their percentage of effective parameters on the Nu number. The results of ANOVA analysis are shown in Table 4. The $F_{0.1,1,47}$ was 251.15 for a significant level of 0.1 (or 90% confidence level). From Table 4, it is clear that the

Tables 3 Variable factor levels

Controllable factors	Level 1	Level 2
A: type of nanofluid	A_1(Al-nanofluid)	A_2 (Cu-nanofluid)
B:concentration	0.55	2.23
C: temperature (°C)	30	40
D: Gz number	21.94	32.91

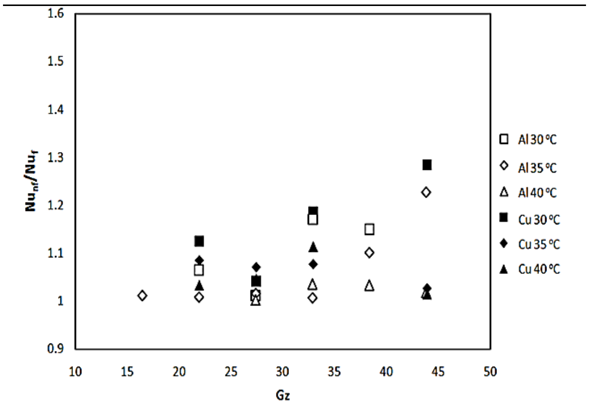

Figure 8 the ratio of Nusselt number in different temperature for 0.55 vol%

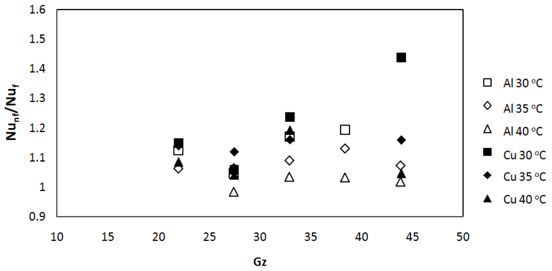

Figure 9 the ratio of Nusselt number in different temperature for 1.12 vol%

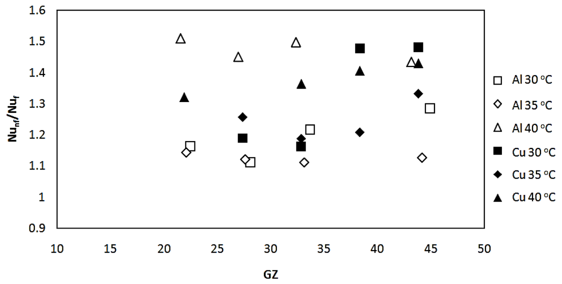

Figure 10 the ratio of Nusselt number in different temperature for 2.23 Vol%

F-values of factor B, factor C, and factor D are greater than $F_{0.05,1,47}$= 251.15. Factor A was not a significant parameter effective on the Nu number.

F-values of A was less than $F_{0.05,1,47}$ = 251.15. A parameter with the most significant effects on the Nusselt number is the Gz number (694.5). Factors C (temperature) and B (concentration) have significant effects on the Nu number. We are confident about 90 up to 100 that these three variables explain the most variations in the heat transfer coefficient. The Type of nanofluid (A) is not an important parameter effective on the Nu number.

5.5 *Correlations for the Nusselt number*

In general, the Nusselt number of nanofluids may be related to the parameters as follows:

$$Nu = f(Gz, \text{wt\%}) \tag{8}$$

By considering the above-mentioned statement, the Nusselt number based on the experimental results of nanofluids in the spiral coil has been correlated by the following equation by using the least squares regression analysis:

$$\text{Nu} = 2.117(1 - \text{wt\%})^{-12.2}\text{Gz}_{\text{nf}}{}^{0.684} \tag{9}$$

Equation 9 fits the experimental data within ±10% error as shown in figure 12 and the correlation is valid for laminar flow with GZ < 2300, and for Al-water and Cu-water nanofluid concentrations less than 2.23 vol. %.

6. Conclusions

The Experimental investigations on the convective heat transfer and the thermal conductivity of Al-water and Cu-water nanofluids were carried out in the laminar regime inside a spiral coil with constant wall temperature. Nanofluids were prepared by one-step method and they were found very stable. The Results showed that adding of nanoparticles to the base fluid increases its thermal conductivity. The Effects of the nanofluid concentrations, Gz number and the constant wall temperature on the Nusselt number were investigated. The Nusselt number increases by increasing both the Gz number and the concentration. However, there are significant

Table 4 ANOVA table for responded data

Source of variation	The Sum of Squares	Degree of freedom (DOF) (*f*)	Mean Squares	F value	P-value
A-Nanofluid	63.87160208	1	63.87160208	72.50825	< 0.0010
B-Concentration	352.5710021	1	352.5710021	400.2453	< 0.0001
C-Temperature	249.5688021	1	249.5688021	283.3152	< 0.0001
D-Gz	611.8266021	1	611.8266021	694.5572	< 0.0001
Residual	30.83	35	0.88		
error	27.16	32	0.85		
Lack of Fit	3.67	11	15.29	18.01	
total	1473.14	47			

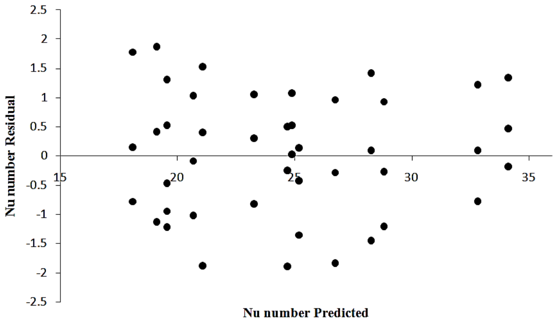

Figure 11 the Residual plot of Nu number

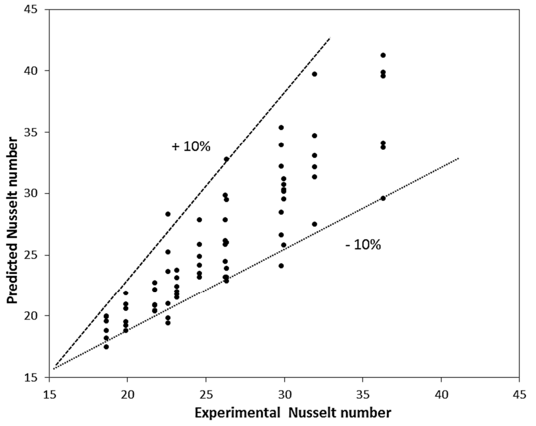

Figure 12 Comparison of experimental Nusselt number with regression equation.

fluctuations due to the secondary flow. An ANOVA analysis showed that the Gz number, temperature, and concentration are the parameters which affect the Nu number significantly.

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