Time Scale Analysis for Prediction of Nusselt Number of Nanofluids Flowing Through Straight Tubes: An Experimental Study

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ABSTRACT: *Because of anomalous heat transport behavior in nanofluids, several possible mechanisms suggested by various authors to explain the thermal conductivity and heat transfer coefficient enhancement lack unanimity. Hence, this research article aims to explore convective heat transfer enhancement mechanisms by correlating them with observed experimental data of nanofluids. The analysis is carried out by comparing the order of magnitude of different diffusion mechanisms for different types of nanofluid systems. Four different types of nanofluids, Al_2O_3/EG-W (0.6, 0.9, 1.2, and 1.5 vol.%.), Al_2O_3/PG-W (1, 1.5, 2, and 2.5 vol.%.), CuO/PG-W (0.25, 0.5, 0.75 and 1 vol.%) and MgO/PG-W (0.3 and 0.66 vol.%) have been studied in this research. A generalized mechanism-based correlation has been proposed to predict the Nusselt number for these nanofluids, for flow through a straight tube under laminar conditions. Results showed that the Brownian motion is very slow in comparison to nano convection-diffusion and heat diffusion. The proposed model predicted the combined data for all the nanofluids studied well within a range of ±5%. Statistical errors of the proposed model were also calculated. Data from other authors were also validated using the proposed correlation, and the parity plot showed that the relationship predicted the data well within a range of ±15%.*

KEYWORDS: *Convective heat transfer; Nusselt number; Brownian motion; Nano convection; Heat Diffusion, Thermophoresis.*

INTRODUCTION

Research in heat transfer characteristic of various nanofluids, experimentally or numerically have been carried out over two decades. The first experiment on convective heat transfer of alumina – water nanofluids were carried by *Pak* and *Cho* [1]. They found that the Nusselt number increased with an increase in nanoparticle

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volume fraction and Reynolds number, whereas the heat transfer coefficient actually decreased by 12%. The reason observed for such contradictory results was high viscosity enhancement in nanofluids. While contrarily, *Eastman et al.* [2] concluded that the convective heat transfer coefficient increased by 15% using CuO nanoparticles with a volume concentration of less than 1%.

Wen and Ding [3] experimentally investigated the heat transfer behavior of nanofluids under laminar conditions and found that the heat transfer coefficient was dependent on the Reynolds number and volume fraction of nanoparticles. The authors noticed that the enhancement was much higher in the entrance region. The reason observed for this behavior was an increase in effective thermal conductivity and migration of particles, further causing a non-uniform assortment of viscosity and thermal conductivity along the tube cross-section. *Heris et al.* [4] also studied the heat transfer of CuO and Al_2O_3/water-based nanofluids through a circular tube under laminar conditions. They observed that the heat transfer coefficient increased with particle volume fraction as well as with Peclet number. They also noted that the Al_2O_3 nanofluids performed better than the CuO nanofluid based on the higher heat transfer enhancement. They concluded that improvement in the thermal conductivity of nanofluids is not only the sole reason for this behavior, but other factors such as dispersion, chaotic behavior of particles, Brownian motion, and particle migration must also be considered for interpretation of results.

Ding et al. [4] studied the heat performance of CNTs nanofluid in the tube. They found that the observed enhancement in the heat transfer coefficient was much higher than the increased effective thermal conductivity, the possible reason which they concluded is the improved thermal conductivity, aspect ratio shear-induced element inflow, and particle rearrangement. Whereas, *Yang et al.* [6] investigated the convective heat transfer performance of graphene nanofluids in the laminar flow, and observed that the increase in heat transfer coefficient was much lower than the enhancement of effective thermal conductivity. They concluded that particle shape and aspect ratio along with thermal conductivity could be considered as possible factors affecting the heat transfer performance which were also discussed by *Ding et al.* [5]. In view of conflicting observations of various authors, further investigations are required in this respect.

Xuan and *Roetzel* [7] proposed two different heat transfer correlations based on two different techniques. The first technique assumed the nanofluids to be single-phase fluid while the other technique treated a nanofluid as a solid-liquid mixture. These proposed models were based on the mechanism of heat transfer enhancement which was further dependent upon the increased thermal conductivity and chaotic particle movement, thereby increasing the energy transfer in the flow. However, there is no concrete experimental analysis for the validation of this model.

Among different research attempts, *Putra et al.* [8] were the first to analyze the natural convective heat transfer of Aqueous CuO and Al_2O_3 nanofluids. They observed a notable decrease in convection heat transfer and this deterioration increased with an increase in volume concentration particularly for CuO nanofluids. They ascribed the deterioration in heat transfer coefficient could be due to particle fluid slip and settlement of nanoparticles as the possible reasons for such degradation. *While Khanafer et al.* [9] theoretically concluded that the natural heat transfer coefficient of nanofluids increases with particle concentration. They proposed a model of heat transfer coefficient for nanofluids, by taking into the effect of solid particle dispersion.

Later *Wen* and *Ding* [10] investigated the thermal performance of aqueous TiO_2 nanofluid under natural convection conditions. Their results exhibited that the natural convective heat transfer coefficient decreased with an increase in nanoparticle concentration. Their finding is in good agreement with that of *Putra et al.* [8] but is contradictory to the observation of *Khanafer et al.* [9]. The author added different reasons for such unexpected results, like convection because of concentration difference, modifications of dispersion properties, and particle surface and particle-particle interactions.

Kim et al. [11] proposed a correlation, by introducing a factor that incorporated the effect of nanoparticle shape factor and volume fraction of nanoparticles, a ratio of thermal conductivity, heat capacity, and density of nanoparticles to the base fluids. According to this model, as the particle volume fraction was increased, the amount of heat transfer in the nanofluid also increased. The observation of *Kim et al.* [11] and *Khanafer et al.* [9] are in good agreement with each other but are contradictory to the observation of *Putra et al.* [8] and *Wen* and *Ding* [10].

Izadkhah et al. [12] studied the rheological properties of graphene oxide-based ethylene glycol water nanofluids at different temperatures using the Non-equilibrium dynamic method. Results showed significant enhancement in viscosity and density w.r.t increase in volume fraction but decrease with temperature. Also, the shear rate analysis results showed that the water ethylene glycol-based graphene oxide nanofluids behaved as a non-Newtonian fluid.

Ardekani et al. [13] experimentally studied the heat transfer characteristics of Ag-water and SiO_2water-based nanofluids flowing through helically coiled geometry under turbulent and uniform heat flux conditions. They observed a significant enhancement in heat transfer of nanofluids in helical coils as compared to straight tubes.

Radkar et al. [14] experimentally analyzed the heat transfer effect of ZnO-water nanofluid. Results showed a significant enhancement in the thermal conductivity of the nanofluid as compared to the base fluid, which further contributed to a significant increment in Nusselt number. The geometrical arrangement of the helical coil is also attributed to this enhancement of heat transfer of nanofluids.

Jumpholkul et al. [15] practically examined the heat transfer behavior of SiO_2 water-based nanofluids flowing through a circular stainless tube equipped with free rotating swirl generators. They presented the result in terms of efficiency index i.e. ratio of nanofluid heat transfer effects to base fluid heat transfer effects. They observed a significant enhancement of 54% in Nusselt number of nanofluids in comparison to the base fluid.

THEORETICAL SECTION

Heat transfer mechanisms

Anomalous diffusion transport in nanofluids could be due to the high surface-to-volume ratio of nanoparticles and the extremely small mass of nanoparticles. Possible mechanisms proposed by various authors to explain this anomalous diffusion transport are:

(1) Brownian motion induced micro convection currents.

(2) Formation of highly conductive paths within aggregates of nanoparticles.

Aggregation is a potential mechanism responsible for the enhancement in heat transfer as compared to mass transfer enhancement because mass diffusivity of the solute in the liquid phase is higher than in the solid phase. These mechanisms cause advection, *via* the fluid motion is locally induced by the Brownian agitation of nanoparticles. Brownian nanoparticles randomly collide to eventually form fractural-like aggregates. Various studies reported in the literature either support or reject the existence of one or all mechanisms. *Wang et al.* [13] proposed the microscopic motion of particles, surface properties, and structural effects as a probable cause for the enhanced heat transfer in nanofluids. Various forces like Vander Waal, Brownian motion, and electrostatic and hydrodynamic forces acting on nanoparticles, have a significant influence on the induction of microscopic behavior of particles. *Keblinski et al.* [17] narrowed down a few mechanisms, which are capable of explaining the phenomena of unusual enhancement of heat transfer in nanofluids. The mechanisms included the clustering effect of nanoparticles, Brownian motion of nanoparticles, ballistic nature of heat transport in nanoparticles, liquid layering on the liquid nanoparticle interface, and thermophoresis.

In view of anomalous heat transport behavior, in nanofluids, a number of possible mechanisms suggested by various authors to explain the thermal conductivity and heat transfer coefficient enhancement lack unanimity. Thus, there is a scope for further work to explore convective heat transfer enhancement mechanisms by correlating available observed experimental data of nanofluids.

Brownian motion

Brownian motion means the haphazard motion of particles dispersed in the fluid. This random dynamic phase of particles affects both the heat and flow nature of the nanofluids. With an increase in temperature, the thermal conductivity increases, and also increases the random particle motion. So smaller particles present in the dispersed medium experience higher motion, therefore smaller particles experience a higher level of Brownian motion. *Pinto* and *Fiorelli* [18] reviewed the recent findings regarding the mechanisms that affect the enhancement of heat transfer behavior of nanofluids. They concluded that the Brownian motion of nanoparticles is the significant mechanism that influenced the thermal behavior of a nanofluid. *Li* and *Peterson* [19] numerically analyzed the effect of the Brownian motion of nanoparticles on the thermal conductivity enhancement. The analysis was carried out for single, adjacent two, and numerous clusters of nanoparticles. Results indicated that the nearby close vicinity two nanoparticles experienced more influence on the temperature field than

the two single nanoparticles far apart, due to interaction. It was also concluded that the Brownian motion is more effective in the multiple nanoparticle clustering. So the results clearly indicated that the Brownian motion is the important key factor for the high thermal conductivity of nanofluids. *Jang* and *Choi* [20] also found that the convection because of the Brownian motion of the nanoparticles is the sole criterion for the observed thermal conductivity enhancement of nanofluids. *Koo* and *Kleinstreuer* [21] presented a theoretical model for effective thermal conductivity of nanofluids, by taking into account various aspects like Brownian motion, thermophoretic and Osmo-phoretic motion. They also concluded that Brownian motion is more significant than the other two for high thermal enhancement. *Whereas Evans et al.* [22] suggested a different argument by proposing that the effect of Brownian motion on thermal conductivity enhancement is very small and it cannot be the only one responsible for the high heat transfer coefficient of the nanofluids. *Nie et al.* [23] theoretically analyzed the enhancement of thermal conductivity of nanofluids to estimate the contribution of Brownian motion. They concluded that the Brownian motion made little effort to the effective thermal conductivity of nanofluids.

Liquid layering on the liquid nanoparticle interface

Two different perspectives about this mechanism exist in the literature. Investigators like (*Yu* & *Choi*[24]; *Leong et al.* [25]) believed that the liquid layering plays an important part in the effective thermal conductivity of nanofluids. They supported that the the solid-like layer acts as a thermal barrier between the base liquid and the solid nanoparticle and hence it's an important mechanism for explaining the abnormal increase in thermal conductivity of nanofluids. Some researchers hold the opposite viewpoint. *Putnam et al.* [26] investigated the thermal conductivity of composites of alumina nanoparticles in polymethylmethacrylate (PMMA) matrices and concluded that the interface layering effect played a negligible role in effective thermal conductivity. Similarly, *Evans et al.* [27] concluded that the interfacial layering confrontation does not significantly affect the thermal conductivity of the composite's nanofluids. *Keblinski et al.* [17] also observed that the rise of the interfacial layer caused the thermal conductivity to increase and this increase is proportional to the size of this layer.

Effect of clustering of nanoparticles

The clustering or agglomeration of nanoparticles is one of the major problems that hinder the enhancement of thermal conductivity. Clustering increases the particle size and becomes denser and results in low thermal conductivity. *Prasher et al.* [28] numerically carried out the Monte Carlo simulations of heat transfer on fractal agglomerates. Results showed that the effective thermal conductivity was because of the clustering of nanoparticles which is a strong function of the chemical aspect of the aggregates and the radius of gyration of aggregates. They also proposed that extreme clustering leads to large sizes thereby sedimentation occurs, which is not suitable for effective thermal conductivity. *Zhu et al.* [29] numerically examined the thermal conductivity of Fe_3O_4 water nanofluids and also concluded that the abnormal behavior in the thermal conductivity of nanofluids is mainly due to heavy clustering and alignment of nanoparticles. *Kakac* and *Pramuanjaroenkij* [30] observed that though clustering of particles up to a certain level contributed to thermal conductivity enhancement at the same time, excessive clustering could also degrade the thermal conductivity. Thus in order to attain maximum enhancement in thermal conductivity, evaluation to obtain an optimum level of clustering needed to be done.

Ballistic nature of heat transport

Heat conduction means heat is transferred internally by the vibrational action of the atoms or molecules. Now, these atoms in a solid structure are connected to each other and thus give rise to vibrations of the whole crystal structure i.e. lattice vibration. This total energy associated with the lattice vibration is quantized. The quantum of this whole energy is either emitted or absorbed by an atom is called a phonon. So this phonon plays an important role in the thermal conduction of the solids. Further in solids, the diffusive nature of heat transfer is predominating if the mean free path of phonons is smaller than the particle size. *Keblinski et al.* [17] demonstrated that the phonons couldn't diffuse into smaller nanoparticles (~10nm), hence the heat transferred is more of ballistic nature than the diffusive one. They also indicated that the ballistic nature of heat transfer was more effective if the nanoparticles lie very close to each other (in order of the thickness of the liquid layer), which make a significant effect on the thermal conductivity of the nanofluids.

Furthermore, they emphasized that the particles are closer to each other due to the Brownian motion, thus enhancing the phonon heat transfer among the particles. *Nie et al.* [23] also studied the phonon mean free path of the suspended nanoparticles. They analyzed that the phonon means free path was effective in the layering structure of one nanometer and most of the fluid molecules remained undisturbed. As a result, they concluded that this mechanism cannot be accounted for the abnormal behavior of the thermal conductivity within nanofluids.

Thermophoresis

Particles can diffuse under the effect of a temperature gradient. This phenomenon is called thermophoresis and is the particle equivalent of the well-known Soret effect for gaseous or liquid mixtures. According to *Buongiorno* [31], Brownian diffusion and thermophoresis are the dominant slip mechanisms in nanofluids. *Ding* and *Wen* [32] evaluated the particle migration in the nanofluid flow through a tube. They considered three factors to be important for determining particle distribution, namely non-uniform shear rate, viscosity gradient, and Brownian motion, while they overlooked the effect of thermophoresis. *Malvandi et al.* [33] theoretically investigated the impact of nanoparticle migration on heat transfer enhancement at film boiling of nanofluids over a vertical cylinder. Brownian motion and thermophoretic diffusivity were considered to study the effect of nanoparticle migration. They indicated that the motion of nanoparticles was from the adiabatic wall (nanoparticle depletion) to the cold wall (nanoparticle accumulation), which led to a non-uniform nanoparticle distribution. They also concluded that the temperature gradient at the heated wall increases as the nanoparticle migration increases, which had a positive effect on the heat transfer rate.

Time scale comparison of different heat transfer mechanisms in Nanofluids

Keblinksi et al. [17] suggested the presence of Brownian motion, liquid layering on the liquid nanoparticle interface, clustering effect of nanoparticles, and ballistic nature of heat transport in nanoparticles, as the possible mechanisms for the enhancement of heat transfer in nanofluids. Based on time scale analysis, the author postulated that the effect of Brownian motion could be ignored as the contribution of the thermal diffusion is greater than the Brownian motion. Similar conclusions were reported by *Eastman* [34] and *Evans et al.* [22]. However, they considered only nanoparticles' Brownian motion in a stationary fluid, neglecting the hydrodynamic effect. The surface-charged state of nanoparticles in suspension could also be an important effect on the enhancement of thermal conductivity. The introduction of the Brownian motion-induced micro convection concept is based on the following time scale analysis. So to sum the probable significant mechanism contributing to the enhancement of convective heat transfer in nanofluids could be the evaluation of the extent of contribution of each machine based on the time scale analysis discussed by various authors are as follows:

a) Time scale for Brownian motion diffusion

Keblinski et al. [17] estimated the time required for both Brownian diffusions as well as for conduction in the liquid. The authors concluded that the time required for energy transport because of conduction in a liquid is lesser in magnitude than the time required for energy transport because of Brownian diffusion, based on the time required by these two mechanisms through an order of magnitude analysis. The distinctive time scale to cover a distance equal to the diameter (d) of the particle due to Brownian motion is given by *Keblinski et al.* [17]

$$\tau_{BD} = \frac{d^2}{6D} = \frac{24\pi\mu r^3}{6k_B T} \quad (1)$$

Where D is the Stokes-Einstein Brownian diffusivity $\left(D = \frac{k_B T}{6\pi\mu r}\right)\left(\frac{m^2}{s}\right)$ and k_B is Boltzmann constant (1.308×10^{-23} J/K), μ is the fluid viscosity (kg/ms) and r is the particle radius (m).

b) Time scale for nano convection-diffusion

Prasher et al. [85] performed a similar investigation regarding the time scale of convection due to particle motion. The convective diffusivity is the same as the kinematic diffusivity (υ) of the liquid which is related to μ as $\nu = \mu/\rho_f$, where ρ_f is the fluid density. Therefore the time (τ_{CD}) required for the effect of convection to be felt at a distance equal to the nanoparticle diameter d, is given as:

$$\tau_{CD} = \frac{d^2}{\nu} = \frac{4r^2\rho_f}{\mu} \quad (2)$$

c)Time scale for Thermal diffusion

Similarly, one can estimate the rate of heat diffusion in a solid or in a stationary fluid by the thermal diffusivity as $\alpha = k/\rho C_p$, where k (W/mK) is the thermal conductivity of the medium and ρC_p is volumetric heat capacity. So based on thermal diffusivity, the time (τ_{HD}) required for heat to diffuse into a liquid by a distance equal to the size of the particle is

$$\tau_{HD} = \frac{d^2}{6\alpha} = \frac{4r^2\rho C_p}{k} \quad (3)$$

d) Time scale for thermophoresis diffusion

Malvandi et al. [33] defined the thermophoresis diffusion coefficient D_T, as

$$D_T = \beta \frac{\mu_f}{\rho_f}\phi \quad (4)$$

Where μ_f and ρ_f, the respective viscosity and the density of the base fluid, ϕ is the particle volume fraction, and $\beta = 0.26\, k_f + 2k_f + k_p$ where k_f and k_p are the thermal conductivity of the base fluid and nanoparticles respectively. The time required for the effect of thermophoresis to be felt at a distance equal to the nanoparticle diameter, d is

$$\tau_{TPD} = \frac{d^2}{6D_T} \quad (5)$$

EXPERIMENTAL RESULTS

The experimental work of heat transfer was previously conducted by the authors for four different types of nanofluids, i.e. Al_2O_3/ EG – Water, Al_2O_3/ PG – Water, CuO/ PG – Water, and MgO/ PG – Water flowing through the straight tube, under laminar conditions, and under constant wall temperature conditions. In order to prepare stable nanofluids, pH of the dispersion was adjusted and the sedimentation technique was used to assess the nanofluid stability. The optimum pH for Al_2O_3/EG-W and Al_2O_3/PG-W nanofluid was found to be 5 and 3 respectively. Both the nanofluids were observed to be stable for about ten days. The optimum pH for CuO nanofluid was found to be 5. The prepared nanofluid was found to be stable for around nine days. Similarly, the optimum value of pH for MgO nanofluid was found to be 10 at which it was found to be stable for seven days. Preparation and characterization of nanofluids have already been discussed in the previous work (*Singh et al.* [35]; *Singh et al.* [36]; *Singh et al.* [37]; *Sharma et al.* [39]; *Sharma et al.* [40] and *Sharma et al.* [41]). The detailed schematic diagram of the experimental setup along with the uncertainty analysis of the independent and derived quantities are presented as supplementary material.

Heat Transfer of nanofluids through a straight tube

Al_2O_3/ PG – Water nanofluids

Fig. 1 shows the behavior of the modified Nusselt number of all the concentrations w.r.t. base fluids for different Peclet numbers. The modified Nusselt number ($Nu_{modified}$) of the nanofluids are higher than those of the base fluid (PG/water (60:40, by wt. %)) and they increase with an increase in the Peclet number as well as with the particle volume concentration. For 1 vol. % nanofluid shows Nusselt number enhancement of 20 % w.r.t base fluid and this increases to 23 % with an increase in Peclet number from 70000 to 145000. Similarly for 2.5 vol. %, this enhancement increases from 25% to 29% in the same Peclet number range. The higher thermal conductivity of nanoparticles is one of the reasons for the better heat transfer performance of these nanofluids. Brownian motion is also responsible for introducing small disturbances in the velocity and in the temperature of the flow because of micro convection formed by the movement of the fluid around the nanoparticles (*Pinto et al.*, [18]).

Al_2O_3/EG-W based nanofluids

Fig. 2 shows the behavior of modified Nusselt number of all the concentrations w.r.t. base fluids for different Peclet numbers. As seen in Fig. 2 the enhancement in nanofluid is more as compared to base fluid, also the enhancement increases with an increase in volume concentration. For volume concentration of 0.6% as the Peclet number increases from 48500 to 83000, the enhancement in Nusselt number increases from 12% to 15.5%, and for volume concentration of 1.5 %, this enhancement increases from 23 % to 28 %, in the same Peclet number range.

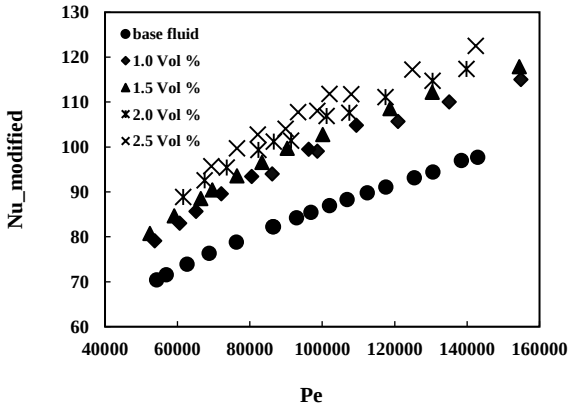

Fig. 1: Experimental modified Nusselt number versus Peclet number for Al_2O_3 - PG/water nanofluid at various volume concentrations.

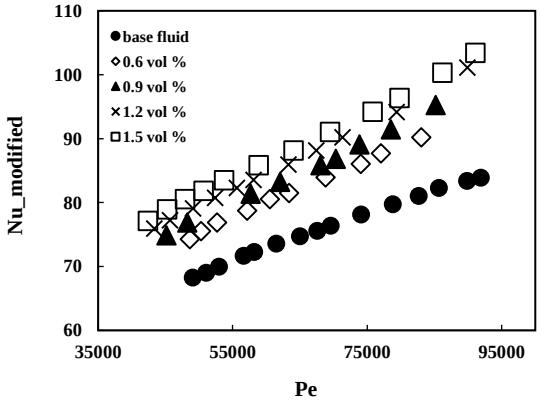

Fig 2: Experimental modified Nusselt number versus Peclet number for Al2O3 - EG/water nanofluid at various volume concentrations.

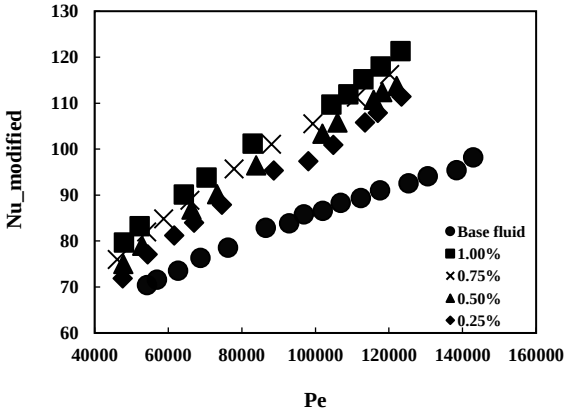

Fig 3: Experimental modified Nusselt number versus Peclet number for CuO - PG/water nanofluid at various volume concentrations.

CuO/PG-W based nanofluids

As shown in Fig. 3, the modified Nusselt number ($Nu_{modified}$) of the nanofluids is higher than those of the base fluid (PG/water (60:40, by wt. %)) and this increases with an increase in Peclet number and with the particle volume concentration. For 1 vol. % nanofluid, in the Peclet number range of 48000 to 123000, the Nusselt number enhancement increases from 19 % to 30 %, and for volume fraction 0.25%, this enhancement increases from 8% to 19%, in the same Peclet number range.

MgO/PG-W based nanofluids

As seen in Fig. 4, the modified Nusselt number ($Nu_{modified}$) of the nanofluids was higher than those of the base fluid (PG/water (60:40 by wt. %)) and it increased with the increase in Peclet number as well as with the particle volume concentration. For 0.66% MgO/PG-W nanofluid system, a significant enhancement of 21% to 29.5% was observed in the Peclet number range of 44500 to 11400. One of the reasons for the better thermal performance of these nanofluids is due to the combined effect of an increase in the nanofluid thermal conductivity and the presence of Brownian motion of nanoparticles.

Data analysis

Based on the different mechanisms as discussed in the previous section, four different time scales for different mechanisms of heat transfer in all nanofluids systems were evaluated. Table 1 shows the comparison of the different diffusion time scales for all the nanofluids studied in the present work.

The above comparison in terms of diffusion time scales for all the cases clearly shows that the movement of nanoparticles due to Brownian motion is too slow to transport a significant amount of heat through a nanofluid. These results are also in good agreement with the findings of *Keblinski et al.* [17]. This comparison of time scales also shows that the rate of nano convection-diffusion is fastest followed by heat diffusion, thus the ratio of the time scale of these two mechanisms was also calculated for all types of nanofluids systems. As can be seen from the table, the ratio of the time scale of heat diffusion to nano convection-diffusion, τ_{HD}/τ_{CD} is ≈ 11 for PG – Water-based nanofluid systems and τ_{HD}/τ_{CD} is ≈ 6 for EG – Water based nanofluid system. Therefore the magnitude of this ratio clearly demonstrates that the nano convection- diffusion

Table 1: Comparison of the different diffusion time scales.

For Al_2O_3/ PG – Water nanofluids (nanoparticle diameter: 80nm), T = 29.5deg C					
Phi	Brownian motion Diffusion (τ_{BD}) (s)	Nano convection diffusion (τ_{CD}) (s)	Heat Diffusion (τ_{HD}) (s)	Thermophoresis Diffusion (τ_{TPD}) (s)	$\frac{\tau_{HD}}{\tau_{CD}}$
0	1.28E-03	9.98E-10	1.13E-08		11.30
0.01	1.38E-03	9.48E-10	1.10E-08	7.08E-06	11.58
0.015	1.44E-03	9.22E-10	1.07E-08	4.72E-06	11.63
0.02	1.47E-03	9.15E-10	1.06E-08	3.54E-06	11.54
0.025	1.56E-03	8.72E-10	1.04E-08	2.83E-06	11.97
For Al_2O_3/ EG – Water nanofluids (nanoparticle diameter: 29nm), T = 33deg C					
Phi	Brownian motion Diffusion (τ_{BD}) (s)	Nano convection diffusion (τ_{CD}) (s)	Heat Diffusion (τ_{HD}) (s)	Thermophoresis Diffusion (τ_{TPD}) (s)	$\frac{\tau_{HD}}{\tau_{CD}}$
0	3.37E-05	2.44E-10	1.39E-09		5.70
0.006	4.21E-05	1.97E-10	1.23E-09	2.79E-06	6.25
0.009	4.60E-05	1.81E-10	1.22E-09	1.86E-06	6.74
0.012	4.76E-05	1.76E-10	1.21E-09	1.40E-06	6.87
0.015	4.88E-05	1.73E-10	1.21E-09	1.12E-06	6.97
For CuO/ PG – Water nanofluids (nanoparticle diameter: 43nm) , T = 31deg C					
Phi	Brownian motion Diffusion (τ_{BD}) (s)	Nano convection diffusion (τ_{CD}) (s)	Heat Diffusion (τ_{HD}) (s)	Thermophoresis Diffusion (τ_{TPD}) (s)	$\frac{\tau_{HD}}{\tau_{CD}}$
0	1.97E-04	2.90E-10	3.26E-09		11.25
0.0025	2.00E-04	2.88E-10	2.88E-09	1.58E-05	9.98
0.005	2.05E-04	2.85E-10	2.87E-09	7.92E-06	10.06
0.0075	2.11E-04	2.80E-10	2.86E-09	5.28E-06	10.22
0.01	2.14E-04	2.79E-10	2.85E-09	3.96E-06	10.25
For MgO/ PG – Water nanofluids (nanoparticle diameter: 50nm) , T = 30.5 deg C					
Phi	Brownian motion Diffusion (τ_{BD}) (s)	Nano convection diffusion (τ_{CD}) (s)	Heat Diffusion (τ_{HD}) (s)	Thermophoresis Diffusion (τ_{TPD}) (s)	$\frac{\tau_{HD}}{\tau_{CD}}$
0	3.12E-04	3.90E-10	4.41E-09		11.31
0.003	3.17E-04	3.85E-10	4.08E-09	6.21E-06	10.58
0.0066	3.11E-04	3.93E-10	3.99E-09	2.82E-06	10.15

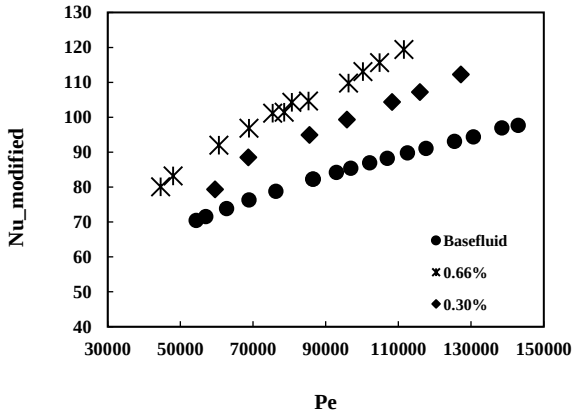

Fig. 4: Experimental modified Nusselt number versus Peclet number for MgO - PG/water nanofluid at various volume concentrations.

and heat diffusion mechanisms are an important factor in order to calculate the heat transfer enhancement rate. Also, this ratio is independent of the type of nanoparticle used in the study, therefore a universal correlation can be proposed which will incorporate the effect of the diffusion ratio along with the volume fraction of the nanofluid system.

So based on the experimental findings, along with the effect of nano convection-diffusion and heat diffusion, the following form of correlation is proposed for all types of nanofluid systems.

$$\frac{Nu_{exp-ST}}{Nu_{The}} = 1 + \alpha \left(\phi \frac{\tau_{HD}}{\tau_{CD}} \right)^{b} \quad (6)$$

Where $Nu_{The} = 1.86\left(Re.Pr.\frac{d}{L}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14}$ is the Seider – Tate equation (*Seider* and *Tate* [42]) for the laminar flow through the straight tube, ϕ is the nanoparticle volume fraction and a and b are the constants, and are calculated using the nonlinear regression technique.

For all the combined nanofluid systems, the values of a and b were calculated as 0.316 and 0.208 respectively.

Different types of statistical parameters like Mean Relative Quadratic Error (MRQE) and Average Relative Error (ARE) were also calculated.

$$MRQE(Mean\ Relative\ Quadratic\ Error) = \sqrt{\frac{\sum\left(\frac{experimental - theroetical}{theroetical}\right)^2}{N-1}} \quad (7)$$

and

$$ARE(Average\ Relative\ Error) = \frac{100}{N}\left|\sum\frac{experimental - theroetical}{theroetical}\right| \quad (8)$$

Where *N* is the number of data points.

Table 2 shows the comparison of statistical errors between the proposed correlation and literature correlation for all studied nanofluids flowing through a straight tube under laminar conditions.

Fig. 5 shows the parity plot of the experimental and calculated values for all nanofluid systems. The present proposed correlation predicted the data of all the nanofluid systems well within ±5%. Further, the applicability present proposed correlation was verified using the experimental data of various authors available in the literature for Al_2O_3 – water nanofluids (*Heyhat et al.* [43]), Al_2O_3 – EG/water nanofluids (*Yu et al.* [44], CNTs – water nanofluids (*Halelfadl et al.* [45]) and Graphene nanoplatelets – EG/water nanofluids (*Selvam et al.* [46]).

Selvam et al. [46] validated his experimental findings using the *Xuan* and *Li* [47] correlation for the pure base fluid instead of using the conventional model (Seider-Tate Equation) available in the literature.

$$Nu_{nf} = 0.4328(1.0 + 11.285\phi^{0.754}Pe^{0.218})Re^{0.333}Pr^{0.4} \quad (9)$$

In order to validate our model using the data of *Selvam et al.* [46], Eq. (9) was used instead of Seider-Tate

Table 2: Comparison of statistical errors.

Correlations	MRQE	ARE (%)
Proposed correlation (Eq.6)	0.02	0.146
Sharma & Syam [38]	0.91	89.08
Xuan & Li [47]	0.78	81.78

the equation in our proposed model. The same comparison is represented graphically as a parity plot in Fig. 6. The proposed correlation predicted the data of other authors well within the range of ±12%. Thus the validity of the proposed correlation can be extended to Al_2O_3 – water nanofluids, CNTs – water nanofluids as well as Graphene nanoplatelets – EG/Water nanofluids.

The proposed correlation, Eq.(6) is further validated on the data reported by other authors (*Bajestan et al.* [48], *He et al.*[49] and *Hwang et al.* [50]), who have reported their studies on heat transfer using nanofluids under laminar flow with constant heat flux conditions. *Bajestan et al.* [48] and *Hwang et al.* [50] worked on Al_2O_3/Water-based nanofluids while *He et al.* [48] worked on TiO_2/Water nanofluid system. These authors validated their experimental findings using the conventional model (*Shah* and *London* [51]) available in the literature.

$$Nu(x) = \begin{cases} 3.302x_s^{-1/3} - 1\,; & x_s \le 0.00005 \\ 1.302x_s^{-1/3} - 0.5\,; & 0.00005 < x_s < 0.0015 \\ 4.264 + 8.68(10^3 x_s)^{-0.506}\exp(-41x_s)\,; & x_s > 0.001 \end{cases} \quad (10)$$

Where $x_s = \frac{x/D}{Re.Pr}$.

In order to validate our proposed correlation for constant heat flux conditions, using data of *Bajestan et al.* [48], *He et al.*[49] and *Hwang et al.* [48]; Eq.(4.10) at xs = L was used instead of the Seider-Tate equation in Eq. (6). The parity plot represents the comparison is shown in Fig. 6. The proposed correlation predicted the data of these authors is well within the range of ±12%.

Statistical parameters, MRQE, and ARE were observed to be 0.065 and 4.38% respectively.

All available correlations in the literature to predict the forced convective heat transfer of nanofluids are system specific and are valid for a certain set of nanofluid systems. The proposed correlation Eq. (6) has a universal character in the sense that it can be used to predict the Nusselt number for forced convective heat transfer for all types of nanofluids flowing under laminar flow conditions.

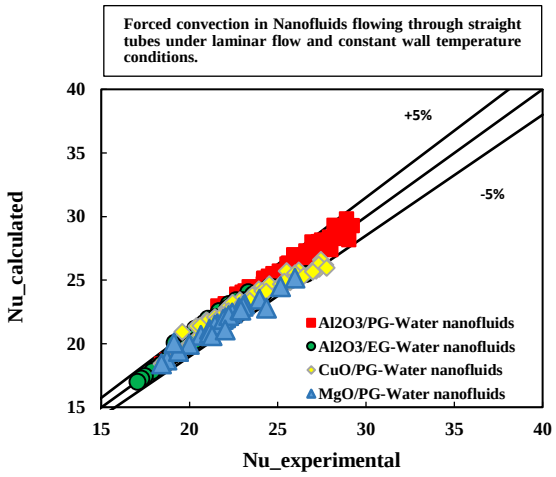

Fig. 5: Parity between Nu_experimental (present data) and Nu_calculated (Eq. (6)).

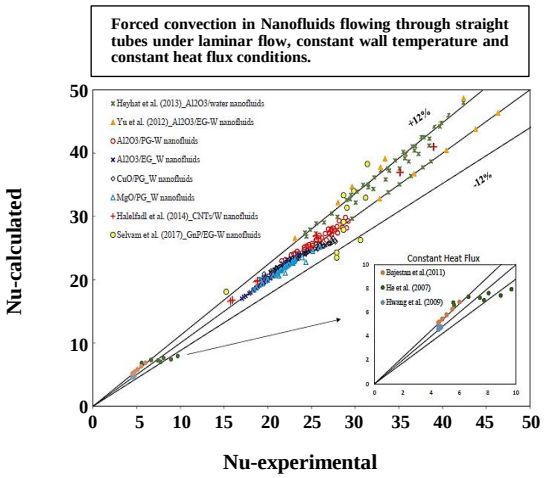

Fig. 6: Parity between Nu_experimental (present and others data) and Nu_calculated (Eq.(4.8)).

CONCLUSIONS

The experimental work presented in this paper mainly focuses mechanism effect on the forced convective heat transfer of four different types of nanofluids flowing under laminar conditions through straight tubes, under constant wall temperature.

● Forced convective heat transfer characteristics, under constant wall temperature boundary condition for Al_2O_3/ EG-W nanofluid (0.6, 0.9, 1.2 and 1.5%), Al_2O_3/ PG-W nanofluid (1.0, 1.5, 2.0 and 2.5%), CuO/PG-W nanofluid (0.25, 0.5, 0.75 & 1.0 vol. %) and MgO/PG-W nanofluid (0.3 and 0.66%), flowing under laminar regime through straight tube was investigated.

● The convective heat transfer coefficient of all the studied nanofluids was found to be greater than that of their corresponding base fluids for both straight tubes as well as helical coils.

● For all the nanofluids, the observed convective heat transfer coefficient, as well as Nusselt number, increased with an increase in Reynolds number as well with particle volume fraction.

● The enhancement in heat transfer of studied nanofluids could be due to various mechanisms: (i) Increase in surface area per unit volume provided by the nanoparticles, the heat capacity, and the apparent thermal conductivity of the fluid. (ii) Presence of Brownian motion and local turbulence caused by random interaction and collision among nanoparticles resulting in flattening of local temperature profile within the nanofluid.

● Further time scale comparisons of various mechanisms, such as Brownian motion diffusion, nano convection-diffusion, heat diffusion, and Thermophoresis were compared for all the combined nanofluids systems. It was concluded that the Brownian motion is very slow in transporting a significant amount of heat transfer. Also, the effect of nano convection and heat diffusion cannot be neglected.

● A new correlation based on the mechanism was proposed, for a straight tube,

$$\frac{Nu_{\exp\_ST}}{Nu_{The}} = 1 + a\left(\phi\frac{\tau_{HD}}{\tau_{CD}}\right)^{b},$$ for the combined nanofluid systems. This correlation predicted the experimental data well within the range of ±5%. Further this correlation, also predicts the data of other researchers also, well within the range of ±12%.

Nomenclature

d	Inside diameter of the tube, m
L	Length of a test section, m
k	Thermal conductivity, W/m.k
v	Fluid velocity, m/s
C_p	Specific heat capacity, J/kg°C
Re	Reynolds number
Pr	Prandtl number

Nu	Nusselt number
Q	Heat transfer rate, W
m	Mass flow rate, kg/s
C	Specific heat, J/kg. °C
T	Temperature of fluid, °C
h	Convective heat transfer coefficient, $W/m^2.K$
A	Surface area, m^2
a,b	Constants

Greek symbols

Φ	Nanoparticle volume fraction
μ	Dynamic viscosity, Pa.s
ρ	Density, kg/m^3

Subscripts

c	Cold fluid
h	Hot fluid
o	Outside
i	Inside
p	Nanoparticle
bf	Base fluid
nf	Nanofluid
EG/W	A mixture of (60:40, by wt. % Ethylene glycol and water)
PG/W	A mixture of (60:40, by wt. % Propylene glycol and water)
SL	Straight tube, laminar condition
CNTs	Carbon nanotubes
MRQE	Mean relative quadratic error
ARE	Absolute relative error

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