INFLUENCE OF ETHYLENE GLYCOL – WATER MIXTURE RATIO ON SiO_2 NANOFLUID TURBULENT FORCED CONVECTION HEAT TRANSFER CHARACTERISTICS

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ABSTRACT

Experiments undertaken with SiO_2 nanoparticles dispersed in ethylene glycol (EG) and water mixtures in the ratios of 60:40 and 40:60 by volume are reported in the literature for heat transfer and friction factor. The influence of concentration and temperature on heat transfer coefficient and friction factor have been determined. In this current study a theoretical model is developed to study the base fluid mixture ratios influence on heat transfer coefficient and flow characteristics in the turbulent range of Reynolds number employing the eddy diffusivity equation of van Driest. Two different base fluid mixture ratios of EG and Water mixed in 60:40 and 40:60 ratio by volume were considered for dispersing SiO_2 nanoparticles. The property Enhancement Ratio of nanofluids for the two mixtures could depict the experimental observation of heat transfer enhancement. The temperature gradient is lower for EGW 40:60 mixture compared to 60:40 mixture. The Prandtl index decreases with an increase in nanofluid concentration and particle density. The numerical results indicate greater values of heat transfer coefficients with EGW of 40:60 mixture ratio compared to 60:40 ratio when plotted with velocity under identical conditions.

INTRODUCTION

The availability of electrical energy for economic growth is a major issue in most of the developing countries of the world. The electrical energy obtained mostly from thermal plants is extensively used by various sectors such as transportation, communication, manufacturing, air conditioning, etc. The traditional heat transfer fluids viz., water, oil, ethylene glycol, propylene glycol are generally used in these industries. The use of fins, micro channels, magnetic and electric fields to improve heat transfer rates have reached extremes. Hence, new and modern technologies which have the potential to enhance thermal properties compared to the conventional working fluids are being developed. The engineered dispersion of solid particles in the form of spheres, tubes, etc of size smaller than 100 nm in base liquids initiated by Choi [1] was named as 'Nanofluid'. The estimation of nanofluid properties in EG base fluid were undertaken for Cu [2], Al_2O_3 [3-5], CuO. [6]. The ongoing trends with EG-Water mixture as base fluid show higher property enhancements specifically at low operating temperatures.

The physical properties of Al_2O_3, CuO, SiO_2 and ZnO nanoparticles suspended in EG-water in 60:40 ratio has been initiated by Vajjha et al. [7-9]. The works of Namburu et al. [10] on the rheological behavior of CuO/EG-water nanofluids have been significant with the data used in the development of correlation for viscosity. Kulkarni et al. [11] estimated the viscosity of SiO_2/EG-water nanofluid and presented an exponential type of correlation for viscosity. Sahoo et al. [12, 13] determined the thermal conductivity and viscosity of SiO_2 and Al_2O_3 nanofluids. Sundar et al. [14] have reported enhancements in the thermal properties of nano-diamond nanofluids and with Al_2O_3/EG-water in different ratios [15] reported maximum enhancements in viscosity for 60:40% nanofluids.

NOMENCLATURE

C_p	[J/kg K]	Specific Heat
d_p	[nm]	Diameter of the particle
f	[-]	Darcy friction factor
k	[W/mK]	Thermal conductivity
Nu	[-]	Nusselt number
Pr	[-]	Prandtl number
Re	[-]	Reynolds number
T	[^oC]	Temperature

60:40	[-]	Ratio by volume

Special characters

α	[m^2/s]	Thermal diffusivity
ε_H	[m^2/s]	Thermal eddy diffusivity
ε_m	[m^2/s]	Momentum eddy diffusivity
ρ	[kg/m^3]	Density
μ	[Pa.s]	Dynamic viscosity
ϑ	[m2/s]	Kinematic viscosity
$\varnothing$	[m]	Volume fraction

Subscripts

B	[-]	Blasius
bf	[-]	Base fluid
nf	[-]	Nano fluid
r	[-]	Ratio

Experiments were undertaken by Vajjha et al. [16] with Al_2O_3, CuO, and SiO_2 nanofluid of particle size up to 100 nm for the estimation of heat transfer coefficients in the turbulent range of Reynolds number for volume concentrations up to 10% in the temperature range of 20-90 ^oC. The experiments were performed with EG-water mixed in 60:40 ratio as a base fluid and reported an enhancement of 81.7% in heat transfer coefficient with Al_2O_3 nanofluid. The authors developed equations for the thermo-physical properties and Nusselt number with their data.

The SiO_2 nanoparticles were used in estimating the convective heat transfer properties and pressure loss by Kulkarni et al. [11] with EG-water mixture as base fluid in 60:40 ratio for a maximum concentration of 10% vol. in the temperatures range of 20-90 ^oC. An enhancement of 16% in heat transfer at 10% concentration was reported with 20 nm particle size at Re = 10000. A comparison of heat transfer and fluid dynamic performance of SiO_2, Al_2O_3 and CuO nanofluids were made by Kulkarni et al. [15] with the aid of the equation developed. Among the three, CuO nanofluids have shown an enhancement of 61% followed by Al_2O_3, SiO_2 with 35% and 18% enhancements respectively. An equation for friction factor was developed using the experimental data of Vajjha et al. [16] given by

$$f_r = \frac{f_{nf}}{f_B} = 1.0\left[\left(\frac{\rho_{nf}}{\rho_{bf}}\right)^{0.797}\left(\frac{\mu_{nf}}{\mu_{bf}}\right)^{0.108}\right] \tag{1}$$

Eq. (1) reduces to Blasius form given in Eq. (2) in the absence of nanoparticles which is given by $f_B = \dfrac{0.3164}{Re^{0.25}}$ (2)

Regression was undertaken by Vajjha et al. [16] with the experimental data to develop an equation for Nusselt number given as

$$Nu = 0.065\left(Re^{0.65} - 60.22\right)\left[1 + 0.0169\left(\frac{\varnothing}{100}\right)\right]Pr^{0.542} \tag{3}$$

The Eq. (3) is valid for 20 $< T_{nf} <$ 90 ^oC; $0 < \phi < 6.0\%$ for CuO and SiO_2 nanofluids and $0 < \phi < 10.0\%$ for Al_2O_3; $d_p <$ 53 nm; 3000 < Re < 16000. Namburu et al. [17] have compared the CFD results for EG-water mixture of 60:40 ratio for a maximum concentration of 6% with the experimental data of Vajjha et al. [16], Kulkarni et al. [11] and reported to be in good agreement. Sarma et al. [18] have undertaken a theoretical analysis with the model they have developed for turbulent flow by introducing a correction factor for the mixing length. Equations for the nanofluid eddy diffusivity of momentum (ε_m/υ) and heat (ε_h/υ) have been proposed. Comparison of the experimental data of Al_2O_3/water nanofluid for a maximum volume concentration of 0.5% with numerical results from the model has been presented. The analysis was later extended to 4% vol. by Sharma et al. [19], [20] employing the eddy diffusivity equation of van Driest. The numerical results were reported to be in good agreement when compared with the experimental data. The numerical values of temperature gradients at the wall determined are reported to be inversely proportional to nanoparticle density for water based nanofluids. This observation implies that particles with low density and high thermal conductivity give higher heat transfer coefficients.

The estimation of nanofluid thermo-physical properties viz., thermal conductivity and viscosity were performed by Sundar et al. [21] for Al_2O_3/EG-Water in 40:60 ratio with a particle size of 36 nm in the temperature range of 20-60^oC for a maximum concentration of 1.5%. Usri et al. [22] have estimated the convective heat transfer coefficient of Al_2O_3 nano particles suspended in EG-water in 40:60 ratio with particle size in the range of 30-50 nm for a maximum concentration of 0.6% at 50 ^oC in the Reynolds range of 1500-18000. They reported an enhancement of 14.6% in heat transfer. In another paper, Usri et al. [23] have estimated the convective heat transfer coefficient of TiO_2 nanoparticles with particle size in the range of 30-50 nm suspended in EG-water in 40:60 ratio for a maximum concentration of 1.5% at 70 ^oC. The experiments were performed under constant heat flux boundary condition for Reynolds number greater than 10,000. A maximum heat transfer enhancement of 34% was reported with 1.5% volume concentration.

Numerical analysis has not been undertaken in the turbulent range of Reynolds number with EG-water mixture. The characteristics of Al_2O_3 nanofluid flow and heat transfer employing van Driest eddy diffusivity equation is undertaken. The present work is to determine the influence of base liquid mixture ratio on the characteristics of nanofluid heat transfer and fluid flow. The theoretical model and the numerical procedure are discussed in [20]. Salient results of the present analysis for two mixture ratios of EG and Water are presented.

In the present study, the influence of two different base liquid mixtures of EG and water mixed in 60:40 and 40:60 ratios by volume are is compared with the numerical results obtained. The results from the analysis is validated with the experimental data of Vajjha et al.[16] for SiO_2/EG-W in 60:40 ratio. The variations of Nusselt number and friction factor with Reynolds number for SiO_2 nanoparticles suspended in EG-W in 40:60 ratio are predicted with the help of numerical analysis.

PROPERTIES OF EG -WATER 60:40 RATIO

Density, specific heat, viscosity and thermal conductivity of the base fluid i.e. EG-W mixture in 60:40 ratio are estimated with Eqs. (4) – (7) developed with the ASHRAE data available [24]. The equations are respectively given by:

$$\rho_{bf} = 1090.6 - 0.32857T - 0.00286T^2 + 5.421\times10^{-19}T^3 \tag{4}$$

$$C_{p\,bf} = 3044.14 + 4.29T - 0.0019T^2 + 1.55759\times10^{-5}T^3 \tag{5}$$

$$\mu_{bf} = 0.0087 - 2.45\times10^{-4}T + 2.8\times10^{-6}T^2 - 1.18\times10^{-8}T^3 \tag{6}$$

$$k_{bf} = 0.33944 + 0.00111T - 1.005\times10^{-4}T^2 + 3.78\times10^{-7}T^3 \tag{7}$$

The bulk properties of nanoparticles used in the development of equations are listed in Table 1.

Table 1. Properties of nanoparticles [25]

Nanoparticle	Thermal Conductivity (W/m.k)	Density (kg/m^3)	Specific Heat (J/kg.k)
CuO	69	6350	535
Al_2O_3	36	3920	773
SiO_2	1.4	2220	745

The properties density and specific heat of nanofluids can be estimated with the mass conservation relation given by:

$$\rho_{nf} = \left(\frac{\varnothing_p}{100}\right)\rho_p + \left(1 - \frac{\varnothing_p}{100}\right)\rho_{bf} \tag{8}$$

$$c_{p,nf} = \left((1-\varnothing/100)\left(\rho C_p\right)_{bf} + (\varnothing/100)\left(\rho C_p\right)_p\right)\Big/\rho_{nf} \tag{9}$$

The properties such as thermal conductivity and viscosity of SiO_2 nanofluids in base liquid EG-water 60:40 are regressed with the available experimental data [8, 26] and given by Eqs. (10) and (11),

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.07\left(1+\frac{\varnothing}{100}\right)^{17.69}\left(1+\frac{T_{nf}}{90}\right)^{-0.06726}\left(1+\frac{d_p}{53}\right)^{-0.1178} \tag{10}$$

$$\frac{k_{nf}}{k_{bf}} = 0.852\left(1+\frac{\varnothing}{100}\right)^{2.608}\left(1+\frac{T_{nf}}{97}\right)^{0.3889}\left(1+\frac{d_p}{77}\right)^{-0.08427}\left(\frac{\alpha_p}{\alpha_{bf}}\right)^{0.04192} \tag{11}$$

The Eqs. (10) and (11) are valid for $0 \le \phi \le 4.0$; $20 \le T_{nf} \le 90\,^oC$; $20 \le d_p \le 50$ with a maximum deviation of 10%. The experimental data of Nusselt number [11, 16] is regressed and Eq. (12) developed valid in the temperature range of 20-90 ^{o}C for a maximum concentration of 4% and for particle diameters lower than 53 nm.

$$Nu = 0.0257Re^{0.8}Pr_{bf}^{\ 0.4}\left(1+Pr_{nf}\right)^{-0.04297}\left(1+\frac{\varnothing}{100}\right)^{5.205} \tag{12}$$

The average deviation of Eq. (12) is estimated to be 7.8% and standard deviation as 9.3% with a few data points deviating from the correlation equation by a maximum of 18%. Substitution of $\varnothing = 0$ and $Pr_{nf} = 0$ in Eq. (12) reduces to the conventional Dittus-Boelter equation with a deviation of 11% applicable for base fluids given by,

$$Nu = 0.0257Re^{0.8}Pr_{bf}^{\ 0.4} \tag{13}$$

PROPERTIES OF EG -WATER 40:60 RATIO

The properties of base fluid EG-W mixture in 40:60 ratio can be evaluated with Eqs. (14) - (17) developed employing ASHRAE [24] data,

$$\rho_{bf} = 1066.79734 - 0.3071T - 0.00243T^2 \tag{14}$$

$$C_{p\,bf} = 3401.21248 + 3.3443T + 0.0000904977T^2 \tag{15}$$

$$k_{bf} = 0.39441 + 0.00112T - 0.00000500323T^2 \tag{16}$$

$$\mu_{bf} = 0.0049 - 1.24\times10^{-4}T + 1.4\times10^{-6}T^2 - 5.6\times10^{-9}T^3 \tag{17}$$

The thermo-physical properties of nanofluid viz., density and specific heat which are required for the determination of heat transfer coefficients can be estimated with the mixture relations given respectively as Eq. (8) and (9). The experimental data available in the literature [22, 23] is used in the development of regression Eq. (18) and (19) for determining viscosity and thermal conductivity respectively considering concentration, temperature and particle size given by,

$$\frac{\mu_{nf}}{\mu_{bf}} = 1.389\left(1+\frac{\varnothing}{100}\right)^{60.68}\left(1+\frac{T_{nf}}{70}\right)^{-0.669}\left(1+\frac{d_p}{50}\right)^{-0.1573} \tag{18}$$

The Eq.(18) is observed to have an average deviation of 6.8% and a standard deviation of 8.5%. The thermal conductivity equation given by Eq.(19) is obtained with an average and standard deviation of 1.9% and 2.8% respectively. It is given by

$$\frac{k_{nf}}{k_{bf}} = 0.9431\left(1+\frac{\varnothing}{100}\right)^{0.1612}\left(1+\frac{T_{nf}}{70}\right)^{0.1115}\left(1+\frac{d_p}{50}\right)^{-0.003986}\left(\frac{\alpha_p}{\alpha_{bf}}\right)^{0.006978} \tag{19}$$

The Eqs. (18) and (19) are valid in the range of $0 \le \varnothing \le 1.5\%$; $20 \le T_{nf} \le 70^oC$; $20 \le d_p \le 50nm$. The experimental data of Nusselt number in base liquid EG-water mixture of 40:60 ratio given by Usri et al. [22, 23] is subjected to regression given by Eq. (20)

$$Nu = 0.0255Re^{0.8}Pr_{bf}^{\ 0.4}\left(1+Pr_{nf}\right)^{-0.02084}\left(1+\frac{\varnothing}{100}\right)^{0.3373} \tag{20}$$

The Eq. (20) is obtained with an average deviation of 7.8% and standard deviation of 9.3%. The equation is valid in the temperature range of 20-70 °C for a maximum concentration of 1.5% for particle diameters lower than 50 nm. The equation reduces to Dittus-Boelter Eq.(13) applicable for pure fluids with $\varnothing = 0$ and Pr_{nf}= 0 in Eq. (20).

RESULTS AND DISCUSSIONS

The Eqs. (10), (11), (18) and (19) developed are validated with the experimental data available in the literature and observed to be in satisfactory agreement.

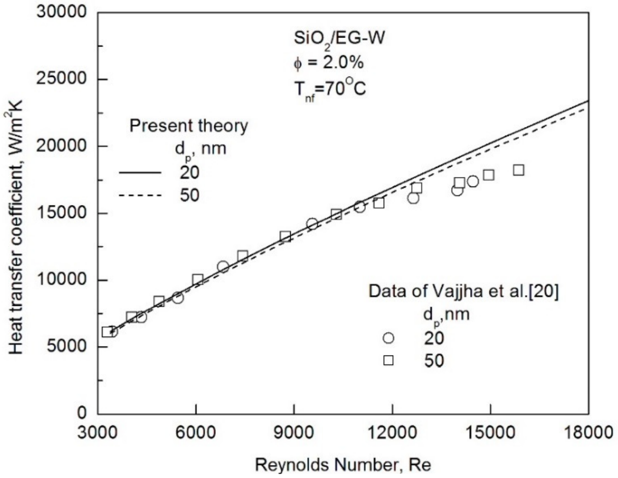

Fig.1. Validation of present theory with experimental data for heat transfer coefficient of SiO_2/EG-W 60:40

Comparison of the experimental data with numerical results for heat transfer coefficient are shown for SiO_2 EG-W in 60:40 base liquid ratio plotted in **Fig.1.** In a similar manner, the results of numerical analysis in **Fig.2** are shown compared with the available Al_2O_3 experimental data for EG-W in 40:60 base liquid [27]. The numerical results can be observed to be in good agreement with the experimental data thus validating the present model.The effect of base liquid ratio on friction factor for SiO_2 nanofluid is shown in **Fig.3** for 4% concentration. The friction factor varies with Reynolds number significantly for the two base liquids which can be observed in **Fig.3**. However, the friction factor with 40:60 ratio is greater compared to values of 60:40 mixture ratio.

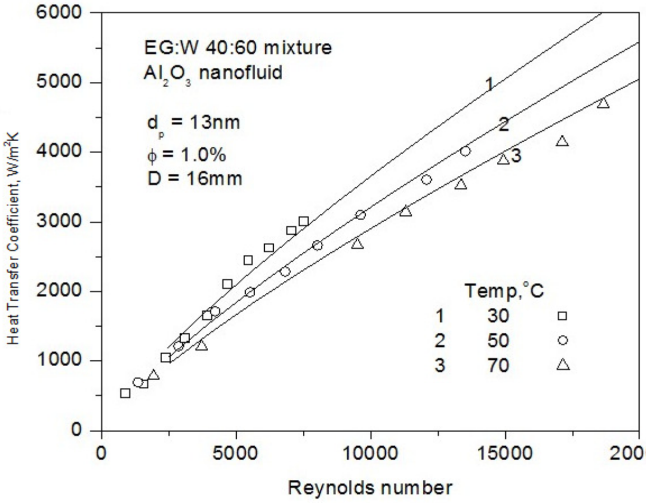

Fig.2. Comparison of experimental data with numerical results for Al_2O_3/EG-W 40:60

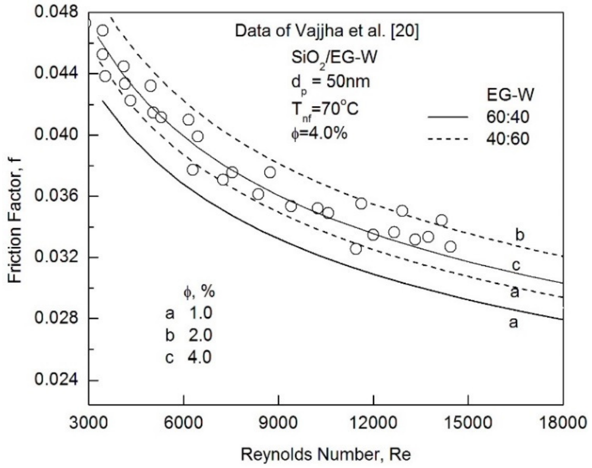

Fig.3. Variation of friction factor with Reynolds number for SiO_2 nanoparticles with two different base fluids

The effect of properties such as viscosity and thermal conductivity on heat transfer Enhancement Ratio, ER [28] is shown in **Fig.4**. ER can be defined as the maximum concentration for possible heat transfer enhancement at a given temperature and particle size. It can be defined as absolute ratio of nanofluid viscosity and nanofluid thermal conductivity and cane be presented as,

$$ER = \left(\frac{\mu_{nf}}{\mu_{bf}} - 1\right) \Big/ \left(\frac{k_{nf}}{k_{bf}} - 1\right) \tag{21}$$

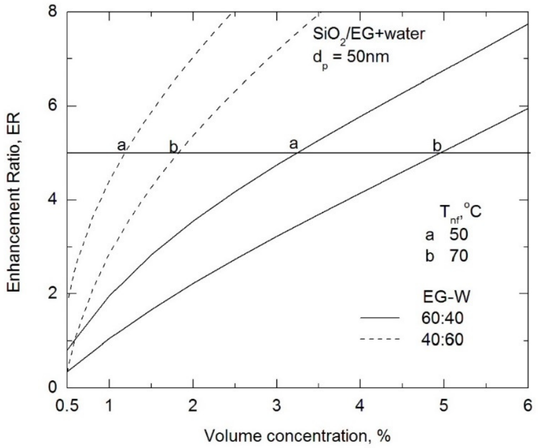

Fig.4. Variation of ER with volume concentration SiO_2 nanoparticles for two different base fluids and two different temperatures

The variation of ER for SiO_2 nanofluid concentration for 50 and 70 °C are shown plotted in **Fig.4** applicable for turbulent flow condition. It can be seen from the **Fig.4** that at 50 °C represented by line 'a' predicts maximum concentration of approximately 1.2 and 3.2% for 40:60 and 60:40 mixture ratios respectively. It implies that if experiments are undertaken with concentrations greater than the maximum values determined, enhancement in heat transfer with concentration is not feasible. This has been reported and validated for single component base liquids viz., water, ethylene glycol, etc.

However, an interesting observation can be made when the two base liquids such as EG and water are mixed in different ratios shown in **Fig.5**. The variation of temperature gradient at a bulk temperature of 50°C with Reynolds number is shown in **Fig.5.**

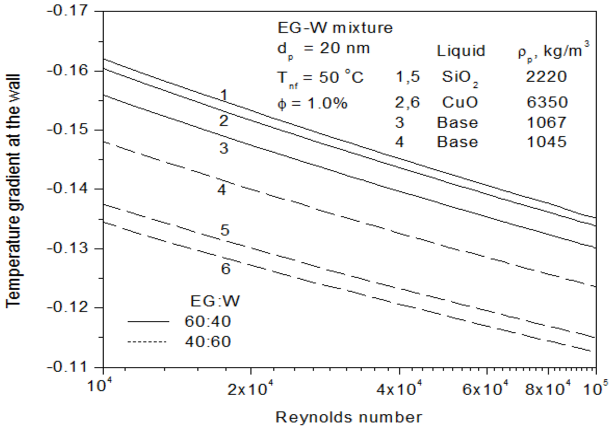

Fig. 5. Variation of temperature gradients with Reynolds number for two different base fluids

The temperature gradient decreases with Reynolds number. At a bulk nanofluid temperature of 50 °C, the temperature gradient obtained from the numerical model for 40:60 ratio has a lower value than 60:40 mixture ratio.

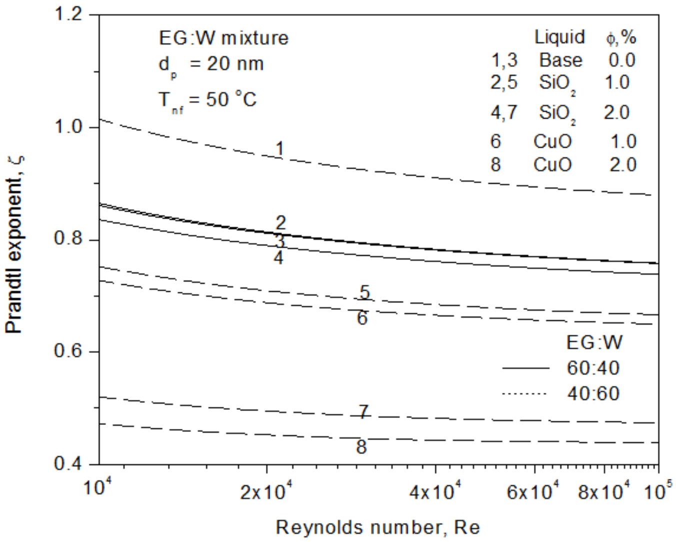

Fig.6 Influence of material, concentration and base liquid on Prandtl index

The influence of base liquid on Prandtl exponent with Reynolds number is shown in **Fig.6**. The values of Prandtl index in base liquid 60:40 are greater than those of 40:60. The values decrease with increase in nanofluid density. It is expected with greater temperature gradients and Prandtl index, the heat transfer coefficients of nanofluid with 60:40 ratio can be higher compared to values with 40:60 mixture ratio.

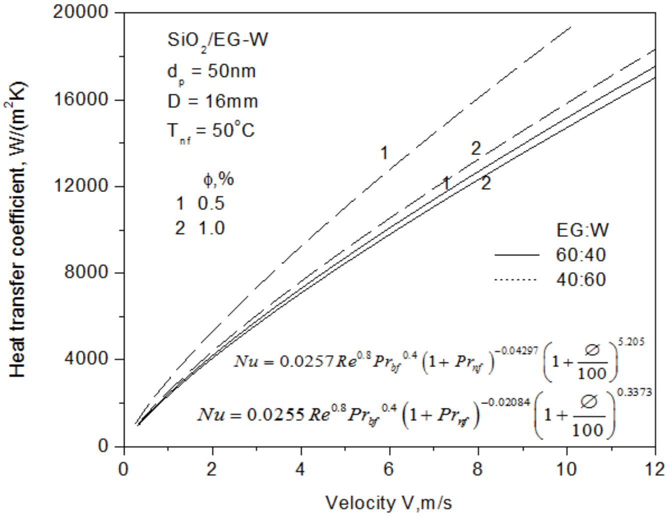

Fig.7. Influence of concentration on heat transfer coefficient at 50 °C

However, the variation of heat transfer coefficient with liquid velocity is shown in **Fig.7** for two concentrations. It has been reported by Kulkarni et al. [11] that a maximum enhancement of 16% is observed with SiO$_2$ nanofluid of 60:40 ratio at 10% concentration. It can be observed that nanofluid of 40:60 ratio predicts greater values compared to nanofluid of 60:40 ratio. It can be inferred that thermal conductivity of the base liquid should be high for obtaining greater values of heat transfer coefficients.

CONCLUSIONS

The heat transfer coefficients with 40:60 mixture ratio is greater than the values with 60:40 mixture ratio under similar operating conditions. The determination of Enhancement Ratio for nanofluids could depict the experimental observations for maximum enhancement in heat transfer. The temperature gradient of EGW 40:60 base liquid is greater than its nanofluids; whereas for EGW 60:40 it is lower. The Prandtl index decreases with increase in nanofluid concentration. The base liquids have higher value of Prandtl index compared to their nanofluids with EG and water mixtures.

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