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Influence of Ethylene Glycol and Water Mixture Ratio on Al_2O_3 Nanofluid Turbulent Forced Convection Heat Transfer

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Abstract: Experiments have been undertaken with Al_2O_3 nanoparticles dispersed in ethylene glycol and water mixture of ratios 60:40 and 40:60. Theoretical analysis have been undertaken in the turbulent range of Reynolds number to determine the effect of liquid mixture ratio on Nusselt number, heat transfer coefficient, nanofluid temperature gradient and enhancement ratio. The heat transfer coefficients with 60:40 mixture ratio is greater than the values with 40:60 mixture ratio. The determination of Enhancement Ratio for liquid mixtures could not depict the experimental observations. The temperature gradient decrease with increase in nanofluid temperature. However at 30°C, higher gradients are observed with 40:60 mixture ratio; while at 70°C the values are lower compared to 60:40.

Index Terms— Nanofluids; Thermo-physical properties, Turbulent flow in a tube; heat transfer coefficient; Friction factor

1 Introduction

Nanofluids are liquids dispersed uniformly mostly with metal or metal oxide spherical particles of nanometer size. The properties of stable nanofluids are reported to be higher than the base liquid in which it is dispersed. Investigations are undertaken with water, ethylene glycol (EG) and their mixtures to determine the properties and heat transfer coefficients of nano fluids. The thermal conductivity of water is higher than EG. However, EG has lower freezing and higher boiling point compared to water. It is reported that higher enhancements in thermal conductivity is obtained with EG compared to water based nanofluids. Hence, investigators have resorted to the use of EG and water mixture in various ratios dispersed with nanoparticles for determining thermo-physical properties and heat transfer coefficients under different flow conditions.

Literature related to estimation of the thermo-physical properties of nanoparticles suspended in EG as base fluid were undertaken for Al_2O_3 [1-3],, CuO. [4], and ZnO [5, 6]. However, a number of investigators undertook experiments with EG-water mixture in the ratio of 60:40. Vajjha et al. [7-9] conducted experiments to determine the thermo physical properties of Al_2O_3, CuO, SiO_2 and ZnO nano fluids. Namburu et al. [10] determined the rheological properties of CuO nano fluid. Kulkarni et al. [11] have undertaken experiments for the viscosity determination of SiO_2 nanofluid. Sahoo et al. [12] in their work with SiO_2 proposed a new correlation to predict thermal conductivity and the results obtained showed good agreement with experimental values with a deviation less than 3.35%. Experimental investigations were carried out to study the rheological behavior of Al_2O_3/EG-W nanofluids by sahoo et al. [13] and they have observed that viscosity increases with an increase in concentration and decreases with increase in temperature. They have proposed two correlations for viscosity as a function of temperature and concentration. Sundar et al. [14] reported enhancements in the thermal properties of nano-diamond nanofluid. All these investigators determined the properties at various concentrations and temperatures.

Experiments for the evaluation of heat transfer coefficients in the turbulent range of Reynolds number were undertaken with Al_2O_3, CuO, and SiO_2 in the temperature range of 20-90°C with particles diameters in the range of 20 to 100nm for a maximum volume concentration of 10% by Vajjha et al. [15]. The experiments were undertaken with EG-water mixture in 60:40 ratio as base fluid and have reported an enhancement of 81.7% in heat transfer coefficient by Al_2O_3 nano fluid. The authors have developed an equation as a function of temperature and concentration for the estimation of thermo physical properties and Nusselt number.

Kulkarni et al. [11] have estimated the convective heat transfer and pressure drop of SiO_2 nanofluids suspended in EG-water mixture of 60:40 ratio for a maximum volume concentration of 10% in the temperature range of 20-90°C. The enhancement in heat transfer is reported to be 16% at 10% concentration with SiO_2 nanofluid dispersed with 20nm size particle at a Reynolds number of 10000%. Vajjha et al. [15] presented Eqs. (1) and (3) for friction factor and Nusselt number respectively based on their experimental data given by

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

In the absence of nanoparticles, the Eq. (1) becomes

$$f_B = 0.3164 / Re^{0.25} \quad (2)$$

which is the conventional Blasius equation. The experimental data of Nusselt is subjected to regression and developed as:

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

The validity of Eq.(3) is for a maximum concentration of 10%

in the temperature range of 20-90ºC for particle diameter lower than 53nm.

Namburu et al. [16] performed CFD analysis for EG-water mixtures for a 6% concentration and compared the numerical results with the experimental data of Vajjha et al. [15], Kulkarni et al. [11] which seems to be in good agreement.

Sarma et al. [17] have developed a model and undertaken a theoretical analysis for turbulent flow by introducing a correction factor for the mixing length. Equations for the nanofluid Eddy diffusivity of momentum $\left(\varepsilon_{nf} / \vartheta_{nf}\right)$ and heat $\left(\varepsilon_{H} / \alpha_{nf}\right)$ have been proposed. Comparison of experimental data of Al_2O_3/water nanofluid for a maximum volume concentration of 0.5% with numerical results from the model has been performed.

The analysis has been extended to 4% vol. by Sharma et al. [18], [19] employing the eddy diffusivity equation of van Driest. The numerical results were observed to be in good agreement 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 high heat transfer rates.

Sundar et al. [20] have performed experiments for the estimation of nanofluid properties such as thermal conductivity and viscosity for Al_2O_3/EG-Water 40:60 ratio with a particle size 36nm for a temperatures ranging from 20-60ºC for a concentration up to 1.5%. Usri et al. [21] in their work on estimating the convective heat transfer coefficient of Al_2O_3 nano particles dispersed in EG-water in 40:60 ratio with particle size 30-50nm for a maximum concentration of 0.6% and the temperature maintained at 50ºC in the Reynolds range of 1500-18000. They reported an enhancement of 14.6% in heat transfer for Al_2O_3 nanofluid at a concentration of 0.6%.

Usri et al. [22] have evaluated the convective heat transfer coefficient of TiO_2 nanoparticles with particle size varying from 30-50nm suspended in EG-water in 40:60 ratio for a maximum concentration of 1.5% at a temperature maintained at 70ºC. 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 for EG-water mixtures. The characteristics of Al_2O_3 nanofluid flow and heat transfer employing the van Driest eddy diffusivity equation is undertaken to determine the properties influencing heat transfer. The present work is to determine the influence of base fluid properties on nanofluid heat transfer and friction factor characteristics. The theoretical model and the numerical procedure is discussed in [19]. Salient results from the numerical analysis is presented in this paper.

2 Base fluid properties of 60:40 EG-W and 40:60 EG-W mixtures

The base liquid properties namely density, specific heat, viscosity and thermal conductivity of EG-W mixture in 60:40 ratio were evaluated from regression analysis undertaken from experimental data available in the literature. The equations are presented as,

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

$$C_{p\,bf} = 3044.135 + 4.2808T - 0.00186T^2 + 0.0000155759T^3 \tag{5}$$

$$k_{bf} = 0.33944 + 0.00111T - 0.0000100528T^2 + 0.0000000377393T^3 \tag{6}$$

$$\mu_{bf} = 0.0087 - 0.000245439T + 0.00000282043T^2 - 0.00000001178T^3 \tag{7}$$

The base fluid properties of EG-W mixture in 40:60 ratio were evaluated from the regression analysis using ASHRAE [23] data,

$$\rho_{bf} = 1066.79734 - 0.3071T_{nf} - 0.00243T_{nf}^2 \tag{8}$$

$$C_{p\,bf} = 3401.21248 + 3.3443T_{nf} + 9.04977\times10^{-5}T_{nf}^2 \tag{9}$$

$$k_{bf} = 0.39441 + 0.00112T_{nf} - 5.00323\times10^{-6}\,T_{nf}^2 \tag{10}$$

$$\mu_{bf} = 0.00492 - 1.24056\times10^{-4}\,T + 1.35632\times10^{-6}\,T_{nf}^2 - 5.56393\times10^{-9}\,T_{nf}^3 \tag{11}$$

3 Nanofluid properties with base liquid as EG-W in 60:40 and 40:60 mixtures

The nanofluid properties such as density and specific heat of Al_2O_3/EG-W in 60:40 ratio are estimated with mass balance relations given by:

$$\rho_{nf} = (\varnothing_p/100)\rho_p + \left(1-\varnothing/100\right)\rho_{bf} \tag{12}$$

$$C_{p\,nf} = \left[\left(1-\phi/100\right)\left(\rho C_p\right)_{bf} + \left(\phi/100\right)\left(\rho C_p\right)_p\right] / \rho_{nf} \tag{13}$$

The properties like thermal conductivity and viscosity of Al_2O_3/EG-water 60:40 nanofluids are evaluated for various particle sizes, temperatures and concentrations. From the experimental data available in the literature, regression analysis has been performed for developing the Eqs. (14) and (15) for viscosity and thermal conductivity respectively which are given as,

$$\mu_{nf} = \mu_{bf} \times 1.07\left(1+\varnothing/100\right)^{17.69}\left(1+T_{nf}/90\right)^{-0.06726} \times\left(1+d_p/53\right)^{-0.1178} \quad (14)$$

$$k_{nf} = k_{bf} \times 0.852\left(1+\varnothing/100\right)^{2.608}\left(1+T_{nf}/97\right)^{0.003889} \times\left(1+d_p/77\right)^{-0.08427}\left(\alpha_p/\alpha_{bf}\right)^{0.04192} \quad (15)$$

The Eqs. (14) and (15) are valid in the range of $0 \le \varnothing \le 4\%$; $20 \le T_{nf} \le 90^{o}C$; $20 \le d_p \le 50nm$ with a maximum deviation of 10%. Similarly, the experimental data of Nusselt is subjected to regression and Eq. (16) is developed which is valid in the temperature range of 20-90^{o}C for a maximum concentration of 4% and for a particle diameters lower than 53nm.

$$Nu = 0.0257 Re^{0.8} Pr_{bf}^{0.4}\left(1+Pr_{nf}\right)^{-0.0194}\left(1+\varnothing/100\right)^{-0.2967} \quad (16)$$

The average deviation is observed to be 7.8% and standard deviation as 9.3% with few exceptions in points which are deviating from the correlation equation by 18%. It can be observed that with the substitution of $\varnothing = 0$ and $Pr_{nf} = 0$ in Eq. (16) simplifies to

$$Nu = 0.023 Re^{0.8} Pr^{0.4} \quad (17)$$

which is the conventional Dittus-Boelter equation applicable for pure fluids.

The thermo physical properties, namely density and specific heat of Al_2O_3/EG-W in 40:60 ratio which are required for the determination of heat transfer coefficients can estimated with mixture Eqs (12) and (13).

The experimental data available for Al_2O_3/EG-W 40:60 nanofluid from the literature 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,

$$\mu_{nf} = \mu_{bf} \times 1.364\left(1+\varnothing\right)^{1.098}\left(1+T_{nf}/70\right)^{-0.6532} \times\left(1+d_p/50\right)^{-0.3712} \quad (18)$$

With an average deviation of 6.8% and standard deviation as 8.5%. The thermal conductivity equation is given in Eq.(19) is obtained with an average deviation and standard deviation of 1.9% and 2.8% respectively. It is given by

$$k_{nf} = k_{bf} \times 0.9431\left(1+\varnothing\right)^{0.1612}\left(1+T_{nf}/70\right)^{0.1115} \times\left(1+d_p/50\right)^{0.3986}\left(\alpha_p/\alpha_{bf}\right)^{0.006978} \quad (19)$$

The Eqs. (18) and (19) are valid in the range of $0 \le \varnothing \le 1.5\%$; $20 \le T_{nf} \le 70^{o}C$; $13 \le d_p \le 50nm$.

The experimental values of forced convection nanofluid Nusselt number in base liquid EG-water mixture in 40:60 ratio is subjected to regression given by Eq. (20) employing the data of Usri et al. [21, 22].

$$Nu = 0.023 Re^{0.8} Pr_{bf}^{0.4}\left(1+Pr_{nf}\right)^{-0.08177}\left(1+\varnothing\right)^{-0.402} \quad (20)$$

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^{o}C for a maximum concentration of 1.5% for particle diameters lower than 50nm. The equation can be reduced to Dittus-Boelter Eq.(17) applicable for pure fluids by substituting $\varnothing = 0$ and $Pr_{nf} = 0$ in Eq. (20)

4 Results and Discussions

Comparisons were made between experimental data of Nusselt number with theoretical results for Al_2O_3 in different base fluids as shown plotted in **Fig. 1.** The theoretical results are observed to be in good agreement with the experimental data thus validating the numerical results.

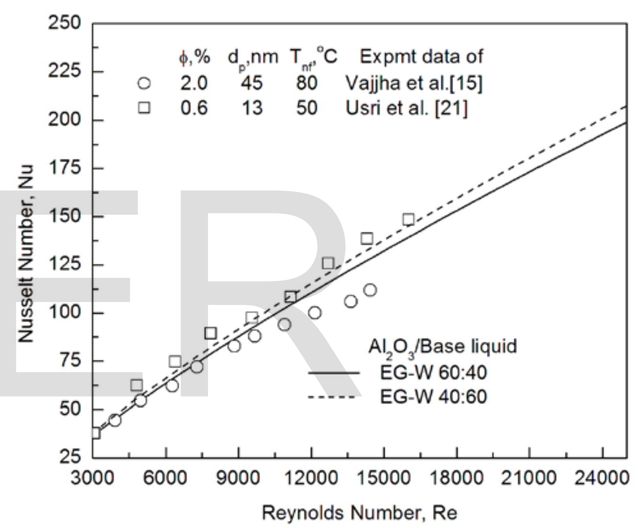

Fig. 1. Comparison of effect of base fluid on Nusselt number

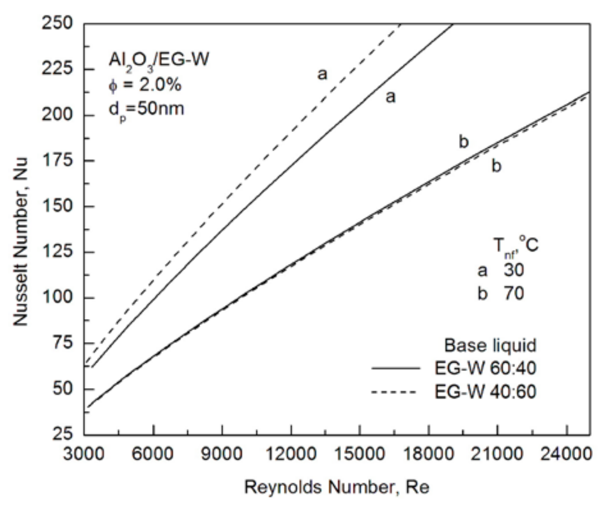

Fig. 2. Comparison of effect of base fluid on friction factor

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Further analysis is undertaken based on the agreement between the experimental data with the numerical results. The influence of temperature on Nusselt number for Al_2O_3 nano fluid for two base liquid ratios is shown plotted in **Fig. 2** for a nano fluid concentration of 2.0%. It can be observed from **Fig.2** that the Nusselt number differs for the nano liquid of 60:40 and 40:60 ratios for a concentration of 2.0% vol. at a temperature of 30°C. However, the deviation between the values for the nano fluids is not observed at 70°C temperature. A comparison of the Nusselt numbers with Al_2O_3/EG-W nanofluid of 40:60 ratio shows relatively higher values at 30°C compared to values with 60:40 ratio

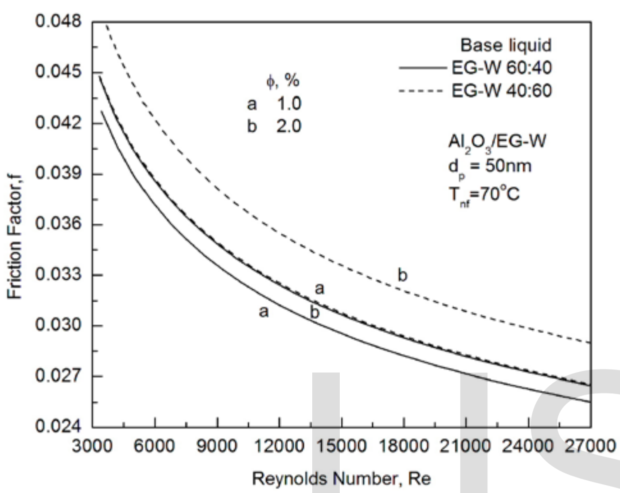

Fig. 3. Comparison of effect of base fluid on friction factor

The variation of friction factor with Reynolds number for Al_2O_3 in two base liquid mixture ratios are shown plotted in **Fig. 3** for two concentrations at a temperature of 70°C. It can be observed that the friction factor varies with Reynolds number significantly for the two base liquids.

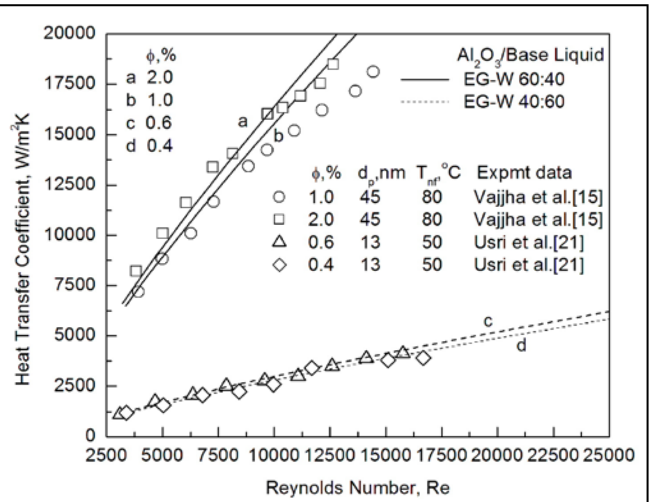

Fig. 4. Comparison of effect of base fluid on heat transfer coefficient

However, the values obtained with 40:60 mixture ratio is greater than with the mixture of 60:40 ratio for the two concentrations presented.

Comparisons of nanofluid heat transfer coefficients suspended in base liquids of different mixture ratio are shown plotted in **Fig.4.** The data for the experimental concentrations undertaken by the investigators is shown plotted along with the theoretical results. It is inferred that the heat transfer coefficients of Al_2O_3/EG-W 40:60 are lower compared to Al_2O_3/EG-W 60:40 mixture ratio. The theoretical results are observed to be in good agreement with the experimental data.

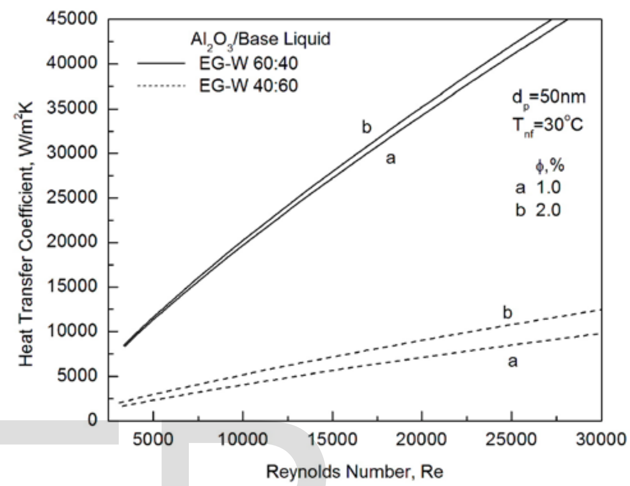

Fig. 5. Comparison of effect of base fluid on heat transfer coefficient

The influence of base liquid mixture ratio on heat transfer coefficient is shown in **Fig. 5** for two concentrations at a bulk temperature of 30°C. It can be observed that the influence of concentration is not significant for both mixture ratios. Further, the enhancement in heat transfer coefficient with concentration of 40:60 mixture ratio is lower compared to values with

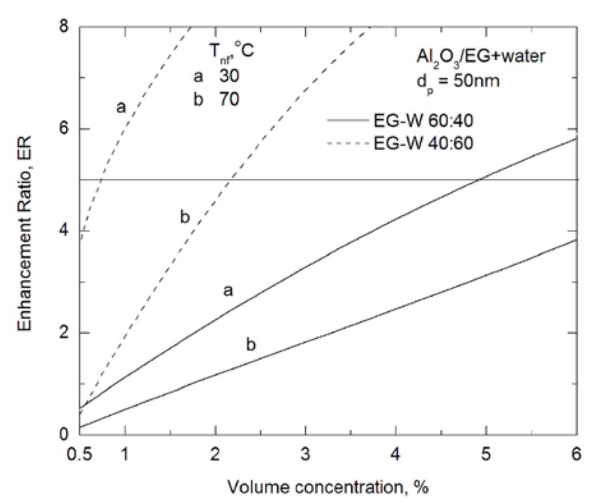

Fig. 6. Comparison of ER with the effect of base fluid gradient

60:40 ratios. This is opposite to the observation made with Nusselt Number where the values with 40:60 ratio are greater than with 60:40 ratio.

The influence of property values of viscosity and thermal conductivity on heat transfer enhancement Ratio, ER [24] is shown in Fig.6. ER is defined as the maximum concentration for heat transfer enhancement at a given temperature and particle size.

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

The variation of ER with Al_2O_3 nanofluid concentration for 30 and 70°C are shown plotted in Fig.6 applicable for turbulent flow condition. From the Fig.6, it is evident that at 30°C represented by line 'a' predicts maximum concentration of approximately 2.0 and 5.0.% for 40:60 and 60:40 mixture ratio respectively. It implies that if experiments are undertaken with concentrations greater than the values obtained, heat transfer enhancement is not feasible. This has been reported and validated for single component of base liquid viz., water, ethylene glycol, etc. However, a different observation is made when two base liquids such as EG and water are mixed in different ratios and compared as reported in Fig.5.

The variation of temperature gradient at bulk temperatures of 30, 50 and 70°C with the Reynolds number is shown plotted in **Fig.7**. The temperature gradient decrease though not significantly with the increase in Reynolds number. At a low temperature 30°C, the temperature gradient for 40:60 mixture ratio has a higher value than with 60:40 mixture ratio. However, a reverse trend can be observed at higher temperature of 70°C.

From **Fig.5** it is evident that heat transfer coefficients are greater for nanofluid of 60:40 ratio in comparison with 40:60 ratio at 30°C for the same concentration. However, in Fig.7, the temperature gradient for 40:60 mixture ratio for 2% nano fluid volume concentration is greater.

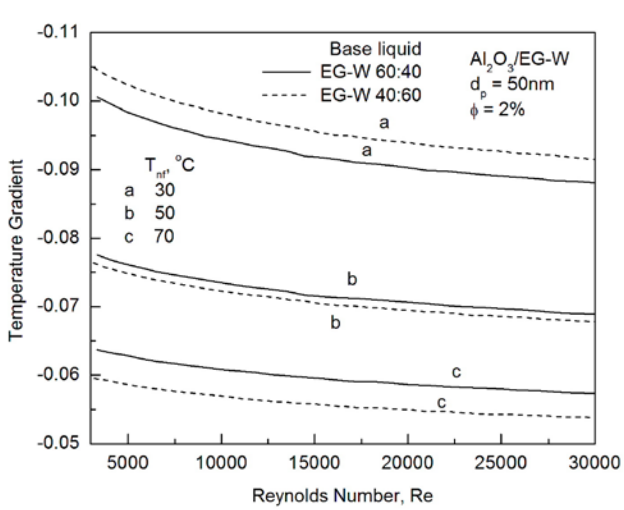

Fig. 7. Comparison of effect of base fluid on temperature gradient

Fig 6 indicates heat transfer enhancements for 40:60 mixture ratio to decrease with increase in temperature. However, it is the opposite for 60:40 mixture ratio at 2.0% volume concentration. Such an observation has not been reported till now.

5 Conclusion

The heat transfer coefficients with 60:40 mixture ratio is greater than the values with 40:60 mixture ratio. The determination of Enhancement Ratio for liquid mixtures could not depict the experimental observations. The temperature gradient decrease with increase in nanofluid temperature. However at 30°C, higher gradients are observed with 40:60 mixture ratio; while at 70°C the values are lower compared to 60:40.

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NOMENCLATURE

Cp	Specific Heat (J/kgK)
dp	Diameter of the particle (nm)
f	Darcy friction factor
k	Thermal conductivity (W/mK)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	Temperature (K)

Greek letters

α	Thermal diffusivity (m^2/s)
ε_H	Thermal eddy diffusivity (m^2/s)
ε_m	Momentum eddy diffusivity (m^2/s)
ρ	Density (kg/m^3)
μ	Viscosity (Pa.s)
ϑ	Kinematic viscosity (m^2/s)
$\varnothing$	Volume fraction

Subscripts

B	Blasius
bf	basefluid
nf	nanofluid
r	ratio

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