Nanofluid Viscosity: An Emerging Research Field

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ABSTRACT

Nanofluids are two phase colloidal suspensions, in which nanoparticles are dispersed within a base fluid. Nanofluids are novel materials, since their thermophysical properties (thermal conductivity, viscosity, etc.) are superior to commercial working fluids. This fact, especially the enhanced thermal conductivity of nanofluids is considered as a very important advantage, since this feature makes nanofluids good candidates for high efficiency requiring heat transfer applications. On the other hand, the pumping power requirement, which is related to the operation cost, is directly proportional to the working fluid viscosity. Therefore, enhanced viscosity of nanofluids can be considered as a drawback for certain applications, since it increases the pumping power requirement. From this point of view, the viscosity of the working fluid should be kept under control, in order to reduce the losses as much as possible. For this purpose, research on the "viscosity of nanofluids" is emerging; however the "viscosity of nanofluids" is not investigated as comprehensively as the "thermal conductivity of nanofluids" and the "heat transfer enhancement obtained with nanofluids". In literature, the viscosity of nanofluids is investigated both theoretically and experimentally. The theoretical investigations on nanofluid viscosity are mainly concerned with the modeling and correlation development, whereas the experimental studies are mainly concerned with the observation of nanofluid viscosity dependent on some factors (mostly temperature and nanoparticle fraction within the nanofluids). The aim of this paper is to emphasize the importance of studying nanofluid viscosity and review a part of the recent literature by making parameter-based comparisons.

1. INTRODUCTION

Nanofluids are novel materials containing nanostructured ingredients (nanoparticles, nanotubes, etc.) within a base fluid. The concept "nanofluid" was coined to S.U.S Choi and his co-workers; and Choi and Eastman defined the nanofluids as: *"new class of engineered fluids, which contain metallic particles with average particle sizes of about 10 nanometers and can be produced by current technology."* (Choi 1995).

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Currently, nanofluids are considered as strong candidates for high efficiency requiring heat transfer applications, due to their superior thermal conductivity compared to commercial working fluids. The enhancement in thermal conductivity comes from the high thermal conductivity of dispersed nanoparticles within the base fluid, mainly. Table 1 provides the thermal conductivities of various solids and liquids (Kakaç 2009).

Since the high thermal conductivity of the working fluid is among the primary requirements of a high efficiency heat transfer application, nanofluid thermal conductivity has been investigated comprehensively. However, viscosity of nanofluids, which is also mostly higher than the commercial working fluids, is critical for applications, since increased viscosity directly relates to increased pumping power requirement, which will possibly limit the potential applications of nanofluids.

Table 1. Thermal conductivities of various solids and liquids (Kakaç 2009)

Solids/liquids	Material	Thermal conductivity (W/mK)
Metallic solids	Silver	429
	Copper	401
	Aluminum	237
Nonmetallic Solids	Diamond	3300
	Carbon nanotubes	3000
	Silicon	148
	Alumina	40
Metallic liquids	Sodium (at 644 ^{o}K)	72.3
Nonmetallic liquids	Water	0.613
	Ethylene glycol (EG)	0.253
	Engine oil (EO)	0.145

The performance of the applications depends on many factors such as the thermophysical properties of the working fluid. Therefore, designing an efficient application is a multivariable task. In Fig. 1, the multi variability of nanofluid systems is illustrated in terms of the nanofluid parameters, nanofluid properties and the heat transfer performance obtained.

As it is seen in Fig. 1, viscosity of nanofluids is a very important parameter for the potential applications of nanofluids; therefore it should be carefully investigated. In order to define the increased viscosity of nanofluids compared to that of the base fluid, the relative viscosity (μ_r) is defined as the ratio of the nanofluid viscosity to base fluid viscosity, i.e. $\mu_r = \mu_{nf} / \mu_{bf}$.
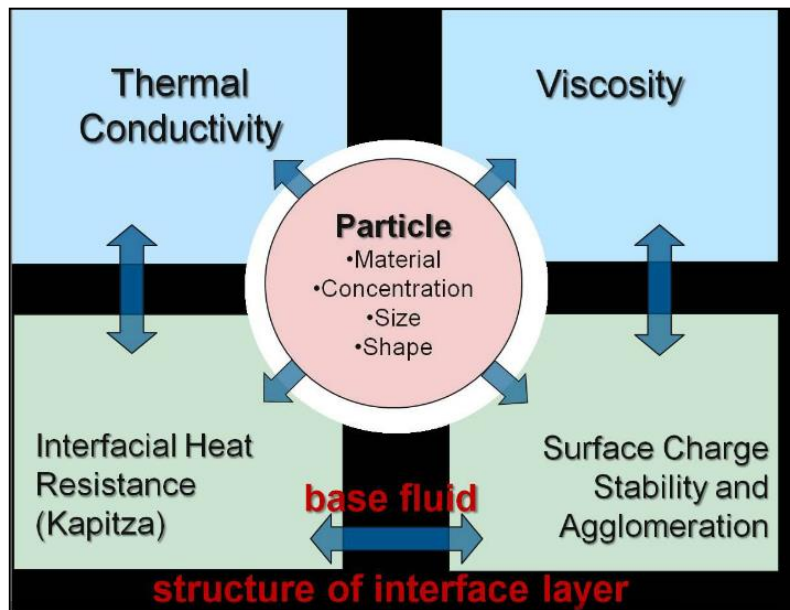
Figure 1. The multi variability of the nanofluid systems: Relation between the engineering parameters and the properties of nanofluids (Timofeeva 2011)

To provide introductory information to the viscosity of conventional suspensions and nanofluids, some important parameters should be introduced at this point. The viscosity of concentrated suspensions is measured as higher than relatively dilute suspensions. Therefore, the viscosity of suspensions is related to the solid content within the suspension. For nanofluids, the amount of nanoparticles suspended within the base fluid is defined as "nanoparticle fraction (φ)", and mostly given by volume, in literature. Another important concept is the size of the particles suspended within the base fluid. For nanofluids containing spherical nanoparticles, the size is defined by their diameters: i.e. "nanoparticle diameter (d_p)".

After this brief introduction on the importance of the viscosity of nanofluids, Section 2 is concerned with the viscosity or relative viscosity estimation of conventional suspensions and nanofluids, whereas in Section 3, parameter based comparisons for the nanofluid viscosity and relative viscosity are presented.

2. VISCOSITY ESTIMATION: CONVENTIONAL SUSPENSIONS & NANOFLUIDS

Viscosity of conventional suspensions depends on many factors (e.g. temperature, solid content within the suspension, pressure, particle shape, particle size, etc.). The relative viscosity of dilute suspensions can be defined as in Eq. (1).

$$\mu_r = 1 + [\eta]\varphi + k_H[\eta]^2\varphi^2 + ... \tag{1}$$

In Eq. (1), $[\eta]$ and k_H are the intrinsic viscosity and Huggin's coefficient, respectively. $[\eta]$ has a typical value of 2.5 for suspensions of hard spheres, and have different

values for different shaped particles. Therefore, deviations of $[\eta]$ from 2.5 indicate deviations from hard-sphere behavior (Goodwin 2004). From this point of view, Einstein (Einstein 1906) and Batchelor (Batchelor 1977) predicted the coefficients of φ and φ^2 as 2.5 and 6.2, respectively (Goodwin 2004).

For more concentrated suspensions, the viscosity can be estimated using Krieger-Dougherty Model (Krieger 1959), which is given as Eq. (2).

$$\mu_r = \left(1 - \frac{\varphi}{\varphi_m}\right)^{-[\eta]\varphi_m} \tag{2}$$

In Eq. (2), φ_m is the maximum concentration at which the flow can occur (Goodwin 2004). The value of φ_m varies from the value of the liquid–solid transition for hard spheres under quiescent conditions (i.e. 0.495 for freezing and 0.540 for melting) to 0.605 corresponding to the flow of hexagonally packed layers at high shear rates (Goodwin 2004).

In the next Section, the nanofluid viscosity is discussed in terms of the nanoparticle volumetric fraction for different nanoparticle shapes, nanoparticle materials and varying nanoparticle clustering levels, and temperature.

3. NANOFLUID VISCOSITY DEPENDENT ON NANOPARTICLE VOLUMETRIC FRACTION AND TEMPERATURE

Nanofluids are literally two phase mixtures, therefore the viscosity of nanofluids can be approached with similar point of views as for conventional suspensions. However, nanofluids mostly have very different behaviors compared to conventional suspensions, which make the use of classical theories for predicting the thermophysical properties of nanofluids mostly insufficient. In nanofluid viscosity literature, the commonly accepted and used viscosity models are called "Classical Models", which are developed for conventional suspensions, not for nanofluids. Einstein Model (Einstein 1906), Krieger-Dougherty Model (Krieger 1959) and Batchelor Model (Batchelor 1977) are some of the Classical Models, and in literature, the validity of the Classical Models is proven to be questionable for nanofluids.

In literature, theoretical and empirical correlations presented specifically for nanofluid viscosity can be found. These correlations are mostly polynomial and seldom exponential. In the present study, some of the nanofluid viscosity and relative viscosity correlations' results and experimental data collected from literature are presented at varying nanoparticle volumetric fractions and temperatures; for different nanoparticle shapes, nanoparticle materials and varying nanoparticle cluster formation levels.

Timofeeva et al. (Timofeeva 2009) investigated the viscosity of Al_2O_3-ethylene glycol & water (50:50) nanofluids and proposed the correlation given below.

$$\mu_r = 1 + A_1 \varphi + A_2 \varphi^2 \tag{3}$$

The coefficients A_1 and A_2 in Eq. (3) have different values for different shaped (i.e. platelet, blade, cylinder, and brick) nanoparticles suspended in the base fluid. A_1 and A_2

were provided as: 37.1 and 612.6 for platelet, 14.6 and 123.3 for blade, 13.5 and 904.4 for cylinder and, 1.9 and 471.4 for brick shaped nanoparticle nanofluids.

In Fig. 2, the relative viscosity of nanofluids is compared for varying nanoparticle volumetric fractions using Eq. (3) and the experimental data of the Al_2O_3-H_2O nanofluid viscosity presented by Turgut (Turgut 2010) and Utomo et al. (Utomo 2012).

The nanoparticle shape effect on the relative viscosity of nanofluids is illustrated in Fig. 2. As it is seen, different relative viscosity values are obtained for different nanoparticle shapes. In addition, the Einstein Model, which is the most widely used Clasical Model in literature, underpredicts the relative viscosity of nanofluids, compared to the other correlations and experimental data presented in the figure. Since the behavior of Einstein Model is presented in Fig. 2, this Model is not included further in the figures providing the following comparisons.
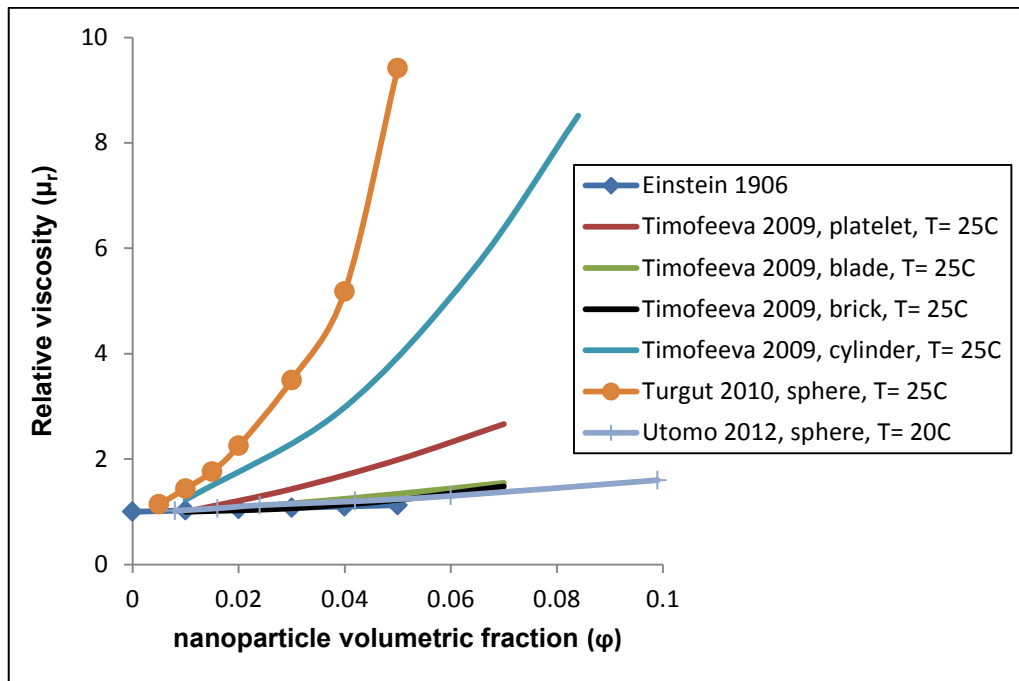

Figure 2. Relative viscosity of Al_2O_3 / water nanofluids for different nanoparticle shapes

Nguyen et al. (Nguyen 2007) proposed correlations for water based Al_2O_3 (d_p= 36 nm) and CuO nanofluids, which are given in Eq. (4) and Eq. (5), respectively.

$$\mu_r = 1 + 0.025\varphi + 0.015\varphi^2 \tag{4}$$

$$\mu_r = 1.475 - 0.319\varphi + 0.051\varphi^2 + 0.009\varphi^3 \tag{5}$$

Similar correlations were proposed by Chevalier et al. (Chevalier 2007) for their experimental data of ethanol based SiO_2 (d_p= 190 nm) nanofluids (Eq. (6)) and Garg et al. (Garg 2008) for their experimental data of Cu-ethylene glycol nanofluids (Eq. (7)).

$$\mu_r = 1 + 8.2\varphi \qquad (6)$$

$$\mu_r = 1 + 11\varphi \qquad (7)$$

Using the abovementioned correlations' results, the relative viscosity of nanofluids is illustrated in Fig. 3.
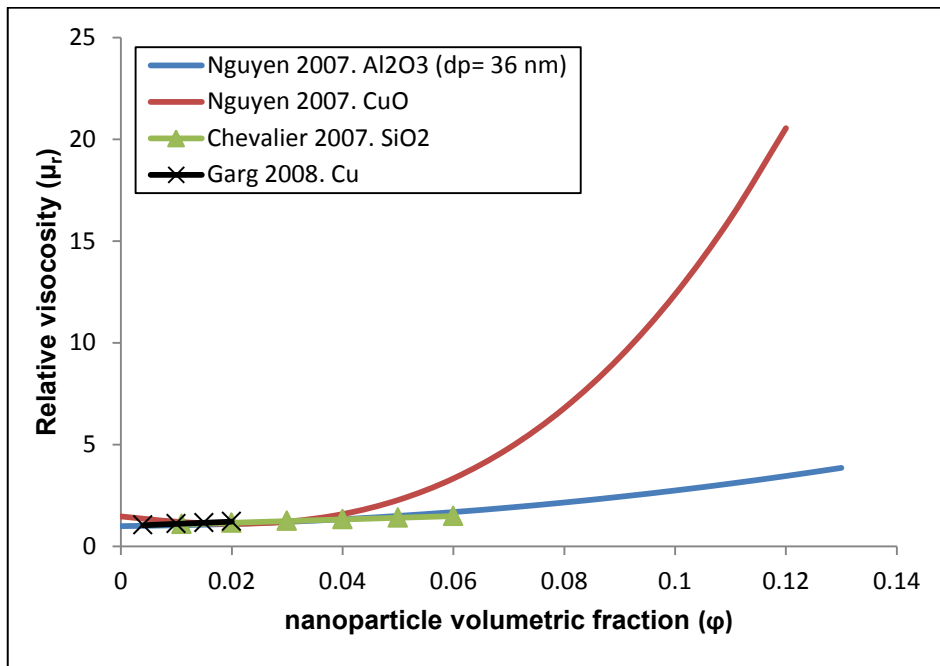

Figure 3. Relative viscosity of nanofluids for different nanoparticle materials

The nanoparticle material effect on the relative viscosity of nanofluids is illustrated in Fig. 3. The nanoparticles are important components of nanofluids, therefore for different nanoparticle materials suspended within base fluids result with different relative viscosities. In addition to the results of the correlations presented in Fig. 3, Tseng and Lin (Tseng 2003) proposed a correlation for the relative viscosity of TiO_2 nanoparticle nanofluids. Using their correlation, approximately 1010 times increase in viscosity is predicted for $\varphi = 0.12$ of TiO_2 nanoparticles, which is considerably higher than the results illustrated in Fig. 3, therefore not included into therein.

Other than the nanoparticle shape and nanoparticle material dependence of nanofluid viscosity, colloidal behavior of nanofluids should also be noted. Colloidal behavior of nanofluids is a dynamic, thus a variable concept. The size of the nanoparticles within the base fluid can vary with time and other ambient parameters. Mostly, the nanoparticles have the tendency to come together and form bigger particles, i.e. clusters (aggregates). The aggregates can be several orders of magnitude larger than the size of the primary particle; therefore aggregation can have a huge impact on the viscosity of the nanofluid.

When the particles within the nanofluid are flocculated, defining the viscosity in terms of the aggregate fraction rather than the particle fraction may be a more sophisticated approach. For this purpose, Chen *et al*. (Chen 2007) modified the Krieger-Dougherty Equation (Eq. (2)) for high shear flows.

$$\mu_r = \left(1 - \frac{\varphi_a}{0.605}\right)^{-[\eta]\varphi_m} \tag{8}$$

In Eq. (8), φ_a is the effective volume fraction of the aggregates and defined as: $\varphi_a = \left(d_a/d_p\right)^{3-D}$, with d_a being the aggregate diameter and D the fractal index of aggregates.

As it can be seen from Eq. (8), increasing the diameter of the aggregate, increases the effective volume fraction of aggregates as well, which in turn will increase the relative viscosity. Therefore, increasing nanoparticle clustering will increase the nanofluid viscosity, and efforts can be made (such as the use of surfactants) to avoid clustering and lower the nanofluid viscosity.

The effect of temperature on fluid viscosity is very dominant, therefore expecting a significant temperature effect on nanofluid viscosity is not wrong. The viscosity of nanofluids decreases with increasing temperature, and such behavior is illustrated in Fig. 4. The temperature and nanofluid viscosity relation mostly follows a non-linear trend, and can be exponential.
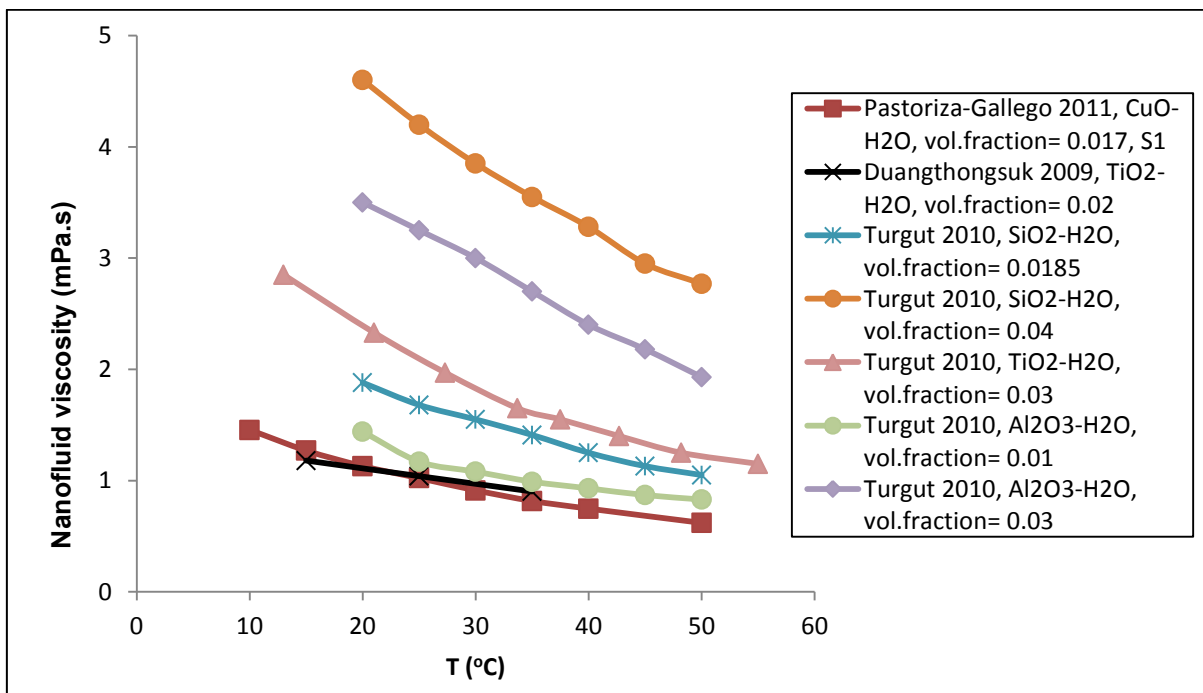

Figure 4. Viscosity of nanofluids for varying temperature

In this Section, the nanofluid viscosity and the relative viscosity are discussed using comparisons at different nanoparticle volumetric fractions and temperatures, for varying nanoparticle shapes, nanoparticle materials and nanoparticle clustering levels. As a conclusion, the nanofluid viscosity and the relative viscosity of nanofluids should be defined dependent on the parameters such as the nanoparticle shape, nanoparticle material, nanoparticle clustering; as well as the nanoparticle volumetric fraction and temperature, in order to have more accurate results of the nanofluid viscosity and thus, relative viscosity.

3. RESULTS

Nanofluids are very popular novel materials, and gain more attention due to their enhanced thermal conductivity, thus improved heat transfer can be obtained with them. As a result of these promising properties of nanofluids, a considerable portion of the nanofluid literature is based on the thermal conductivity of nanofluids and heat transfer enhancement with nanofluids. However, the viscosity of nanofluids is of great importance for the potential applications, and deserves attention as well.

In the comparisons provided in the previous Section, the nanofluid viscosity and relative viscosity is discussed for varying nanoparticle shapes, nanoparticle materials and nanoparticle clustering levels at varying nanoparticle volumetric fractions and temperatures. The comparison with respect to nanoparticle volumetric fraction and temperature is important, since a significant part of the literature handles the nanofluid viscosity (and thus, relative viscosity) based on these parameters.

From the comparisons presented in the previous Section, it can be concluded that, the nanoparticle shape and nanoparticle material are also important parameters and can have significant effect on nanofluid viscosity, as well as the nanoparticle volumetric fraction and temperature. In addition, the nanoparticle clustering should be taken into consideration for more sophisticated estimation of nanofluid viscosity, thus relative viscosity.

REFERENCES

Batchelor, G.K. (1977), "Effect of brownian-motion on bulk stress in a suspension of spherical-particles." *J. Fluid Mech.*, Vol. **83**, 97–117.

Chen, H., Ding, Y. and Tan, C. (2007), "Rheological behaviour of nanofluids." *New J Phys.,* Vol **9**, 367.

Chevalier, J., Tillement, O. and Ayela, F. (2007), "Rheological properties of nanofluids flowing through microchannels." *Appl. Phys. Lett.*, Vol. **91**, 233103, 1-3.

Choi, S.U.S. and Eastman, J.A. (1995), "Enhancing thermal conductivity of fluids with nanoparticles", *ASME International Mechanical Engineering Congress & Exposition, November 12-17,* San Francisco, CA*.*

Einstein, A. (1956), "A new determination of molecular dimensions (Ann Phys (4), **19**, 1906, pp. 289-306. Corrections, ibid., **34**, 1911, pp. 591-592,) in *Investigations on*

the theory of, the brownian movement." Edited with notes by: R. Fürth, Translated by: A.D. Cowper, Dover Publications, Inc, New York, 37-62.

Garg, J,. Poudel, B., Chiesa, M., Gordon, J.B., Ma, J.J., Wang, J.B., Ren, Z.F., Kang, Y.T., Ohtani, H., Nanda, J., McKinley, G.H. and Chen, G. (2008), "Enhanced thermal conductivity and viscosity of copper nanoparticles in ethylene glycol nanofluid.", *J. Appl. Phys.*, Vol. **103**, 074301, 1-6.

Goodwin, J.W. (2004), *Colloids and Interfaces with Surfactants and Polymers – An Introduction*, John Wiley & Sons Ltd, West Sussex, England.

Kakaç, S. and Pramuanjaroenkij, A. (2009), "Review of convective heat transfer enhancement with nanofluids." *Int J Heat Mass Tran.*, Vol. **52**, 3187–3196.

Krieger, I.M. and Dougherty, T.J. (1959), "A Mechanism for Non-Newtonian flow in suspensions of rigid spheres." *T Soc Rheol.*, Vol. **3**, 137-152.

Nguyen, C.T., Desgranges, F., Roy, G., Galanis, N., Maré, T., Boucher, S. and Angue Mintsa, H. (2007), "Temperature and particle-size dependent viscosity data for water-based nanofluids – Hysteresis phenomenon." *Int JHeat Fluid Flow.*, Vol. **28**, 1492–1506.

Timofeeva, E.V., Routbort, J.L. and Singh, D. (2009), "Particle shape effects on thermophysical properties of alumina nanofluids." *J Appl Phys.*, Vol. **106**, 014304, 1-10.

Timofeeva, E.V., Yu, W., France, D.M., Singh, D and Routbort, J.L. (2011), "Nanofluids for heat transfer: an engineering approach." *Nanoscale Res Lett.*, Vol. **6**: 182.

Tseng, W.J. and Lin, K-C. (2003), "Rheology and colloidal structure of aqueous TiO_2 nanoparticle suspensions." *Mat Sci Eng A.*, Vol. **355**, 186-192.

Turgut, A., (2010), *"Investigation of thermophysical properties of nanofluids"*, PhD thesis, submitted to the Graduate School of Natural and Applied Sciences of Dokuz Eylül University, Izmir, Turkey.

Utomo, A.T., Poth, H., Robbins, P.T. and Pacek, A.W. (2012), "Experimental and theoretical studies of thermal conductivity, viscosity and heat transfer coefficient of titania and alumina nanofluids." *Int J Heat Mass Tran.*, Vol. **55**, 7772–7781.