Nanofluids Analysis Model - Basis for Comparison and Prediction

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Abstract
Nanofluids are made of both a base fluid and a volume fraction of dispersed nanoparticles, with sizes within the range of 1-100nm. Nanofluids demonstrates specific thermo-physical properties and characteristics and some authors deal with nanofluid as being colloids, mainly due to their non-Newtonian behavior, viscoelastic properties, shear stress behavior, etc. The most common nature of nanoparticles are different types of carbons (e.g. diamonds, graphite, carbon nanotubes, etc.), metallic (e.g. Gold, Copper, Silver, Steel, etc.) or even metallic oxides (e.g. CuO, SiO, Al_2O_3, ZnO, etc.). There is still a challenge to accurately compare the available nanofluid results usually due to the fact that some nanofluid types have just a few data available, which would demand additional experimental data for proper correlations and comparisons among them. From all nanofluid types currently available in the literature it is clear that both Al_2O_3 (alumina) and CuO (copper oxide) are the most common nanoparticles and water is the most common base fluid. Taking into account the material compatibility for several applications, the Al_2O_3–water nanofluid has become a very interesting and widely studied nanofluid followed by CuO-water nanofluid. There are also several CuO-water nanofluid publications with some different nanoparticle sizes available for research and it is reasonable that nanoparticle size represents one of the aspects to be taken into consideration when the analysis of thermal enhancements are in focus. Therefore, this study aims to evaluate some available results in literature for CuO-water nanofluids, by comparing the obtained thermal enhancement results with the nanoparticle sizes used in each respective study, as well as the direct influence on their viscosities, in order to provide some statistical trend lines through the reviewed data by using a CuO-water nanofluid based on their particular characteristics.

Keywords: thermal enhancement, viscosity, statistical model, nanofluids.

Introduction
The study of nanofluids has been increasing during the last years since Choi (1995) established the term "nanofluids". Several nanofluid thermo-physical properties and their characteristics have been experimentally tested and also studied such as viscosity, density and thermal conductivity. Thermal conductivity is the most widely studied nanofluid property due to the fact that it is related to the increase on the nanofluid thermal enhancement levels obtained when compared to the base fluids alone. Nanofluids demonstrate specific thermo-physical properties and characteristics in such a way that some authors deals with nanofluid as being colloids, mainly due to their non-Newtonian behavior, viscoelastic properties, shear stress behavior, etc. Related to the base fluids used for nanofluid preparations the most commons found in literature are: water, ethylene glycol and engine oil. There are a reasonable number of publications released in the last decade, which increased particularly in the last years. They put together both the base fluids and nanoparticles generating some nanofluids types which were tested, for aerospace and electronics applications, also extending to automotive.
According to Das et al. (2008) nanofluids are made of a base fluid with dispersed nanoparticles in the range size of 1 to 100nm, thus the statement of nanoparticle size range differs nanofluids from other fluid types. The study of nanoparticle size and its influence on thermal conductivity has been of great interest for several authors (Das et al., 2008). Some theoretical and experimental studies included the impact of nanoparticles sizes in their models. It is common to find out in the literature the estimative of average nanoparticle sizes through statistical data over a range of nanoparticle size distribution. It is unusual to obtain the exact same nanoparticle size and shape over a whole volume concentration (vol. %) of nanoparticles used in any nanofluids. In the preparation process of a nanofluid, the nanoparticle sizes can vary according to some other parameters as for example, volume concentration and time of sonication. Thus, the thermal enhancement related to nanoparticle size is affected by these parameters as well (Bhupender et al., 2014). Pastoriza-Gallego et al. (2010) experimentally studied the influence of CuO nanoparticle sizes in other parameters as density and viscosity whose are both related to thermal enhancement of CuO-water nanofluids. Nguyen et al. (2007) studied the influence of CuO nanoparticle size and temperature in CuO-water nanofluid viscosity

levels. Corcione (2011) prepared a correlating equation for thermal conductivity based on several available data in literature, including CuO-water nanofluids. The outcomes demonstrated that as nanoparticle size increases thermal enhancement ratio decreases and vice-versa. Wang et al. (2009) demonstrated that surfactants applied to CuO-water nanofluids tends to decrease the nanoparticle size distribution due to better nanofluid stabilization and elimination of agglomerations. The impact on the nanofluid's viscosity will directly result in a more or less pumping power to drive the working fluid throughout the system, which can be an issue especially in long lines thermal management cycles. The addition of solid nanoparticles will cause a direct impact on nanofluid viscosity that must be carefully consider by the system's designer.

Thermal conductivity and viscosity models related to nanoparticle sizes

From the available literature, it is possible to mention some of the thermal conductivity models applicable for CuO-water nanofluids. Table 1 gives a summary of these models and demonstrates how each model consider nanoparticle size influence on the thermal conductivity or thermal enhancement ratio. Table 2 summarizes some results from the literature, which somehow correlates nanoparticle size with thermal enhancement. The thermal conductivity determination depends on other parameters besides nanoparticle sizes, thus in a trial to compare them, it was also included volume fraction, temperature and sonication time. It is clear that even using the same CuO nanoparticle sizes and, in some cases, the same volume fractions and sonication times, different results were obtained by different authors. This is directly related to differences on the nanoparticle preparation from one study to another, as well as differences on nanoparticle shape and average sizes. In order to bring all results to the same base of comparison, those variables need to be treated in a statistical model that will allow the results comparison in a proper way.

Table 1 – A summary of thermal conductivity models.

Author	Model	Comments
Maxwell [1881]	$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f + 2\emptyset_p(k_p - k_f)}{k_p + 2k_f - \emptyset_p(k_p - k_f)}$	Based on spherical particles, random suspensions which must be under conduction solution theory through stationary conditions.
Hamilton [1962]	$\frac{k_{eff}}{k_f} = \frac{k_p + (n-1)k_f + (n-1)\emptyset_p(k_p - k_f)}{k_p + (n-1)k_f - \emptyset_p(k_p - k_f)}$	For high concentrantions of spherical particles under conditions of differential effective medium (DEM) theory.
Prasher et al. [2005]	$k_{eff} = (1 + ARe^m Pr^{0.333}\emptyset_p)\left[\frac{k_p + 2k_f + 2\emptyset_p(k_p - k_f)}{k_p + 2k_f - \emptyset_p(k_p - k_f)}\right]k_f$	Obtained from Maxwell model and included the effects of convection generated by the Brownian motion
Koo and Kleinstreuer [2005]	$k_{eff} = k_{static} + k_{Brownian}$ $k_{static} = \frac{k_p + 2k_f + 2\emptyset_p(k_p - k_f)}{k_p + 2k_f - \emptyset_p(k_p - k_f)}$ $k_{Brownian} = 5 \times 10^4 \beta \emptyset_p \rho_p C_p \sqrt{\frac{k_B T}{\rho_p D}}(T, \emptyset_p)$	Considers the effects of surrounding liquid motion with random nanoparticles movement. Based on static Maxwell theory and dynamic effect of Brownian motion
Yu-Choi [2003]	$k_{eff} = \frac{k_p + 2k_f + 2(k_{pe} - k_f)(1+\beta)^3 k_f}{k_{pe} + 2k_f - (k_{pe} - k_f)(1+\beta)^3}$ $k_{pe} = \frac{2(1-\gamma) + (1+\beta)^3(1+2\gamma)\gamma}{-(1-\gamma) + (1+\beta)^3 + (1+2\gamma)}k_p$ $\gamma = k_{lr}/k_p$	It was based on Maxwell model but additionally taking in account the effects of nanolayer thickness and thermal conductivity (TC) parameters

Table 2 – Different nanoparticle sizes applied in CuO-water nanofluid and their respective thermal enhancement ratios.

Author	CuO Nanoparticle Size (nm)	Thermal Enhancement ratio	Volume fraction (vol. %)	Temperature (°C)	Sonication time (h)
Karthikeyan et. al [2008]	8	1,02	0,02	20	0,5
	8	1,08	0,09	20	0,5
	8	1,13	0,1	20	0,5
	8	1,19	0,3	20	0,5
	8	1,25	0,8	20	0,5
	8	1,316	1	20	0,5
Nemade et. al [2016]	33	1,197	0,5	55	1
	42	1,134	0,5	55	0,75
	46	1,124	0,5	55	0,5
	53,5	1,087	0,5	55	0,25
Khedkar et al. [2012]	25	1,05	0,01	26	1,5
	25	1,12	0,02	26	1,5
	25	1,13	0,03	26	1,5
	25	1,16	0,04	26	1,5
	25	1,17	0,05	26	1,5
	25	1,32	0,075	26	1,5
Wang et al. [2009]	42,5	1,08	0,02	25	not informed
	42,5	1,1	0,04	25	
	42,5	1,11	0,1	25	
	42,5	1,125	0,15	25	
	42,5	1,16	0,4	25	
Priya et al. [2012]	50	1,02	0,004	28	6
	50	1,06	0,008	28	6
	50	1,1	0,012	28	6
	50	1,13	0,016	28	6
	50	1,05	0,004	50	6
	50	1,16	0,008	50	6
	50	1,25	0,012	50	6
	50	1,32	0,016	50	6
	50	0,95	0,004	55	6
	50	1,24	0,008	55	6
	50	1,33	0,012	55	6
	50	1,43	0,016	55	6

Following the same trend line, Table 3 shows the viscosity models available as well as their considerations on the direct impact on the nanofluid. Since the nanoparticle addition on the base fluid directly changes the nanofluid's dynamic viscosity, the pumping power required to drive the nanofluid throughout the system may present higher levels than those predicted previously. Therefore, the gain obtained with the increase on the thermal conductivity and thus on the overall heat transfer capability augmentation, may not be worth applying the nanofluid due to the increase on the pumping power and the direct impact on the increase of the energy required to run the cycle. As a consequence, the entire system would require to be redesigned increasing its hydraulic diameter to compensate the increase on the pressure drop, which could negatively impact the overall design costs. However, the tradeoff must be carefully considered and most often, redesigning the system will be well paid off due to the increase on the overall heat transfer compared to the drawback caused by the increase on the pressure drop.

Conclusions

The following conclusions can be derived from this study:

- Nanoparticle size can vary according to sonication time;
- As nanoparticle sizes increases, the thermal conductivity decreases;

Table 3: Viscosity models.

AUTHOR	EQUATION	REMARKS
Einstein 1906	$\mu_{eff} = (1 + 2.5\varphi_p)\mu_f$	Based on phenomenological hydrodynamic equation for infinitely dilute suspensions of spheres with no interaction between spheres Works well for volume concentration max. (φp) of 2%.
Brinkman 1952	$\mu_{eff} = \frac{1}{(1+2.5\varphi_p)^{2.5}}\mu_f = (1 + 2.5\varphi_p + 4.375\varphi_p^2 + \cdots)\mu_f$	Extended Einstein model by considering effect of addition of one solute molecule to an existing solution
Buongiorno 2006	$\mu_{eff} = (1 + 39.11\varphi_p + 533.9\varphi_p^2)\mu_f$ $\mu_{eff} = (1 + 5.45\varphi_p + 108.2\varphi_p^2)\mu_f$	Curve fitting from experimental data of Al_2O_3-water nanofluid
Nguyen et al. 2007	$\mu_{eff} = \mu_f . 0.904e^{0.148\varphi_p}$ $\mu_{eff} = (1 + 0.025\varphi_p + 0.015\varphi_p^2)\mu_f$	Curve fitting from experimental data of Al_2O_3-water nanofluid
Chen et al. 2007	$\mu_{nf} = \mu_{bf}(1 + 10.6\varphi + (10.6\varphi)^2)$	Adjusted model for experimental versus theoretical data by considering the rheological effects of shear-rate
Nguyen et al. 2007	$\mu_{eff} = \mu_f . 0.904e^{0.148\varphi_p}$ $\mu_{eff} = (1 + 0.025\varphi_p + 0.015\varphi_p^2)\mu_f$	Curve fitting from experimental data of Al_2O_3-water nanofluid
Chen et al. 2007	$\mu_{nf} = \mu_{bf}(1 + 10.6\varphi + (10.6\varphi)^2)$	Adjusted model for experimental versus theoretical data by considering the rheological effects of shear-rate
Kulkarni et al. 2007	$ln\mu_{eff} = A\left(\frac{1}{T}\right) - B$ $A = 20587\varphi_p^2 + 15857\varphi + 1078.3$ $B = -107.12\varphi_p^2 + 53.54\varphi + 2.8715$	Curve fitting from experimental CuO-water: 5% < φp < 15%; dp=29nm; 278 < T (K) < 323; shear rate = 100 l/s
Namburu et al. 2009	$\log(\mu_{eff}) = Ae^{-BT}$ $A = -0.29956\varphi_p^3 + 6.738\varphi_p^2 - 55.444\varphi + 236.11$ $B = (-6.4745\varphi_p^3 + 140.03\varphi_p^2 - 1478.5\varphi + 20341$	Curve fitting from experimental data of Al_2O_3-EG nanofluid 1% < < 10% ; dp=53nm ; 278 < T(K) < 323
Abedian et al. 2010	$\mu_{nf} = \frac{\mu_{bf}}{(1 - \left(\frac{5}{2}\right)\varphi)}$	Extension of Einstein equation for obtaining good agreements in volume concentration ranges of up to 18-20% in suspension system non-interacting spherical particle.
Meybodi et al. 2015	$\mu_{nf} = \mu_{bf} . \frac{A_1 + A_2 . \exp\left(\frac{\varphi}{S}\right) + A_3 . \left(exp\left(\frac{\varphi}{S}\right)\right)^2 + A_4 . \left(exp\left(\frac{\varphi}{S}\right)\right)^3}{A_5 + A_6 . \frac{\ln(S)}{T} + A_7 . \frac{(\ln(S))^2}{T}}$ A1 = 1.3354064976 × 10^2 A2 = −3.4382413843 × 10^2 A3 = 2.9011804759 × 10^2 A4 = −7.8993120761 × 10 A5 = 9.1161630781 × 10^−1 A6 = 3.2330142333 × 10 A7 = −1.1732514460 × 10	Model obtained from experimental data which takes into account Volume concentration, size of nanopartcles and temperature.

- Further investigation is necessary for better understanding the impacts over each size percentage of the statistical nanoparticle size distribution versus thermal and pressure drop enhancement ratios;
- Nanoparticle size can vary according to surfactants application for nanofluid stabilization;
- The addition of solid nanoparticles in the base fluid directly cause the increase on the nanofluid's viscosity, which impacts on the increase of the overall pressure drop. Proper consideration on the tradeoff related to the enhancement of the overall thermal capability of the system compared to the increase of the pumping power must be done in order to better evaluate the application of nanofluids.

Better evaluation regarding the nanofluid design and application needs to be performed, in order to better predict their thermal behavior, along with the impact on the overall pressure drop. A statistical model that considers the most important aspects of a nanofluid can highly contribute to this purpose.

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