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A REVIEW ON THE THERMOPHYSICAL PROPERTIES OF WATER-BASED NANOFLUIDS AND THEIR HYBRIDS

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ABSTRACT

A nanofluid is a solid–liquid mixture which consists of nanoparticles and a base liquid. Nanoparticles are basically metal (Cu, Ni, Al, etc.), oxides (Al_2O_3, TiO_2, CuO, SiO_2, Fe_2O_3, Fe_3O_4, $BaTiO_3$, etc.) and some other compounds (SiC, $CaCO_3$, graphene, etc.) and base fluids usually include water, ethylene glycol, propylene glycol, engine oil, etc. Conventional fluids have poor heat transfer properties but their vast applications in power generation, chemical processes, heating and cooling processes, electronics and other micro-sized applications make the re-processing of those thermo fluids to have better heat transfer properties quite essential. Recently, it has been shown that the addition of solid nanoparticles to various fluids can increase the thermal conductivity and can influence the viscosity of the suspensions by tens of percent. The thermophysical properties of nanofluids were shown dependent on the particle material, shape, size, concentration, the type of the base fluid, and other additives. Therefore, a comprehensive analysis has been performed to evaluate the thermophysical properties of nanofluids due to variations of nanoparticle volume concentration. Actually, it is shown that no model is able to predict the thermophysical properties of nanofluids precisely in a broad range of nanoparticle volume fraction. Also, a review on hybrid nanofluids is inserted, even if the research is at the very beginning. As a conclusion, the results indicated that further work is needed due to a large uncertainty in termophysical properties method of estimation.

KEYWORDS: hybrid nanofluid, thermal conductivity, Nusselt number, oxide nanoparticles, viscosity

1. Introduction

The past decade has seen the rapid development of the science and technology of nanofluids in many respects but the present research is mostly focused on their thermal conductivity. Choi [1] in 1995 showed from a series of calculations that the thermal conductivity of a fluid can be enhanced by adding nanoparticles. However, nanofluid viscosity also deserves the same attention as thermal conductivity.

Due to the very small size and large specific surface areas of the nanoparticles, nanofluids have superior properties like high thermal conductivity, minimal clogging in flow passages, long-term stability, and homogeneity [2]. Conventional fluids such as ethylene glycol (EG), water and oil have poor heat transfer properties but their vast applications in power generation, chemical processes, heating and cooling processes, transportation, electronics, automotive and other micro-sized applications make the re-processing of those thermo fluids to have better heat transfer properties quite essential.

Viscosity describes the internal resistance of a fluid to flow and it is an important property for all thermal applications involving fluids [3]. The pumping power is related with the viscosity of a fluid. In laminar flow, the pressure drop is directly proportional to viscosity. Hence, viscosity is as important as thermal conductivity in engineering systems involving fluid flow [4].

Lee *et al.* [5] measured the thermal conductivity of Al_2O_3 (mean diameter 38 nm) and CuO (mean diameter 23.6 nm) nanofluids in water and ethylene glycol up to about 4% volumetric concentration, using the transient hot-wire method. Their experimental results showed that for a copper oxide-ethylene glycol nanofluid the thermal conductivity can be enhanced by more than 20% for a particle volumetric concentration of 4%. Their measured thermal conductivity of CuO nanofluids with that obtained from the model of Hamilton and Crosser [6] did not agree. Therefore, the Hamilton-Crosser model, which was originally developed for microparticles, was found to be inadequate to predict the thermal conductivity of nanofluids correctly and new correlations were necessary.

Eastman *et al.* [7] measured the thermal conductivity of Cu nanoparticle of mean diameter <10 nm in ethylene glycol. They found that the effective thermal conductivity increased by up to 40% with approximately 0.3% volumetric concentration of Cu nanoparticles over the base fluid.

Das *et al.* [8] presented the temperature dependency of thermal conductivity of nanofluids with water-based CuO and Al_2O_3 nanoparticles of average particle diameter 28.6 nm and 30.4 nm respectively. Their measured thermal conductivity values of CuO-water nanofluid of 4% volumetric concentration exhibited an increase from 14 to 36% over the base fluid with temperature increasing from 21 °C to 51 °C. They also showed that at temperatures above the room temperature, the Hamilton and Crosser [6] model failed to predict the correct values of thermal conductivities for both nanofluids, consistently under-predicting the correct values.

Wang *et al.* [9] presented a model based on the fractal theory for the determination of the effective thermal conductivity of nanofluids. They compared the fractal model prediction to experimental data with 50 nm CuO particles in DI water of less than 0.5% volumetric concentration. They mentioned that beyond this dilute limit, the model needs to be refined by taking into account possible deposition effect. Koo and Kleinstreuer [10] derived a model for the effective thermal conductivity of nanofluids that combines the conventional static part represented by Hamilton-Crosser equation plus a dynamic part due to the Brownian motion. This model includes the effects of particle size, volume concentration, temperature, properties of the base fluid and the nanoparticles and the motion of the surrounding fluid moving with the particles. Using their model of effective thermal conductivity and viscosity, Koo and Kleinstreuer [11] showed through a numerical laminar flow analysis that there was an increase in the heat transfer performance of micro-heat sinks with the addition of CuO nanoparticles of particle diameter 20 nm and particle concentration of up to 4% in the base fluids of both water and ethylene glycol.

Viscosity and rheological properties are essential parameters to know for practical applications of nanofluids. In this study, it has been shown that a great amount of research has been done considering the viscosity of nanofluids. However, it does not seem to be sufficient to estimate any standard about the viscosity of nanofluids, as there are some inconsistencies among the published results [2, 12-21]. For example, some authors reported that nanofluids were Newtonian fluids [2, 12], while others observed a non-Newtonian behavior [12-16].

Some authors showed that relative viscosity is independent of temperature [12] and some authors showed that the viscosity of nanofluids decreases non-linearly or exponentially [19-21] with the increase of temperature.

From another perspective, some researchers showed viscosity increasing linearly with the increase of volume concentrations, while others showed a nonlinear trend [12, 13]. Also, the same nanofluids with the same concentration demonstrate different viscosity enhancement. Debates also exist about the particle size effect on the viscosity of nanofluids.

In this study, a comprehensive analysis was performed in order to compare and evaluate different models for thermal conductivity and viscosity for three different oxide nanofluids.

2. Thermophysical properties

Using classical formulas derived for a two-phase mixture, the density, specific heat capacity and thermal expansion coefficient of the nanofluid under consideration as a function of the particle volume concentration and individual properties can be computed using the following equations, respectively:

$$\rho_{eff} = \varphi\rho_p + (1-\varphi)\rho_f \qquad (1)$$

$$(\rho c_p)_{eff} = \varphi(\rho c_p)_p + (1-\varphi)(\rho c_p)_f \qquad (2)$$

$$(\rho\beta)_{eff} = \varphi(\rho\beta)_p + (1-\varphi)(\rho\beta)_f \qquad (3)$$

However, the transport properties of nanofluid: dynamic viscosity and thermal conductivity are not only dependent on nanoparticle volume fraction, but are also highly dependent on other parameters, such as particle shape (spherical, disk shape or cylindrical), size, mixture combinations and slip mechanisms, surfactant, etc. Studies showed that viscosity, as well as thermal conductivity increases by use of nanofluid compared to base fluid. So far, various theoretical and experimental studies have been conducted and various correlations have been proposed for the dynamic viscosity and the thermal conductivity of nanofluids.

2.1. Thermal conductivity

Theoretical efforts and modeling of the thermal conductivity enhancement mechanisms in nanofluids have not come up with a universal theoretical model that carefully predicts the thermal conductivity for a variety of nanofluid compositions. The macroscopic effective medium theory (EMT) introduced by Maxwell [22] and further developed for non-spherical particle shapes by Hamilton and Crosser [6] predicts that thermal conductivity of two component heterogeneous mixtures is a function of the conductivity of pure materials, the composition of the mixture and the manner in which pure materials distributed throughout the mixture.

A review on existing models relevant to aluminum oxide (Al_2O_3), copper oxide (CuO) and titanium dioxide (TiO_2), dispersed in water is depicted in Table 1.

***Table 1.** Correlations on thermal conductivity*

Model	Reference	Year	Correlation	Relevant information
Theoretical	Maxwell [22]	1881	$\frac{k_{eff}}{k_f}=\frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)}$	spherical particles
	Bruggemann [23]	1935	$\frac{k_{eff}}{k_f}=\frac{1}{4}\left[(3\phi-1)\frac{k_p}{k_f}+(2-3\phi)\right]+\frac{k_f}{4}\sqrt{\Delta}$ $\Delta=\left[(3\phi-1)^2\left(\frac{k_p}{k_f}\right)^2+(2-3\phi)^2+2(2+9\phi-9\phi^2)\frac{k_p}{k_f}\right]$	spherical particles
	Hamilton and Crosser [6]	1962	$\frac{k_{eff}}{k_f}=\frac{k_p+(n-1)k_f+(n-1)\varphi(k_p-k_f)}{k_p+(n-1)k_f-\varphi(k_p-k_f)}$ $=4.97\varphi^2+2.72\varphi+1$	k_p / k_f > 100
	Wasp [24]	1977	$\frac{k_{eff}}{k_f}=\frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)}$	
	Davis [25]	1986	$\frac{k_{eff}}{k_f}=1+\frac{3(k-1)}{(k-2)-\phi(k-1)}\left[\phi+f(k)\phi^2+O\phi^3\right]$	f(k) = 2.5 for k = 10 f(k) = 0.5 for k = ∞
	Lu and Lin [26]	1996	$\frac{k_{eff}}{k_f}=1+a\phi+b\phi^2$	For k = 10: a = 2.25, b = 2.27 For k = ∞ a = 3.00, b = 4.51
	Bhattacharya et al. [27]	2004	$\frac{k_{eff}}{k_f}=\frac{k_p}{k_f}\phi+(1-\phi)$ $k_p=\frac{1}{K_BT^2V}\sum_{j=0}^{n}(Q(O)Q(j\Delta T))\Delta T$	
	Xue [28]	2005	$\frac{k_{eff}}{k_f}=\frac{1-\phi+2\phi\frac{k_p}{k_p-k_f}\ln\frac{k_p+k_f}{2k_f}}{1-\phi+2\phi\frac{k_f}{k_p-k_f}\ln\frac{k_p+k_f}{+2k_f}}$	
Experimental	Li and Peterson [29]	2006	$\frac{k_{eff}-k_f}{k_f}=0.764\phi+0.0187(T-273.15)-0.462$	Al_2O_3/water

			$\frac{k_{eff}-k_f}{k_f}=3.761\phi+0.0179(T-273.15)-0.307$	CuO/water
	Buongiorno [30]	2006	$\frac{k_{eff}}{k_f}=1+2.92\phi-11.99\phi$	TiO_2/water
	Timofeeva *et al.* [31]	2007	$k_{eff}=(1+3\phi)k_f$	Al_2O_3/water
	Avsec and Oblak [32]	2007	$\frac{k_{eff}}{k_f}=\left[\frac{k_p+(n-1)k_f+(n-1)(1+\beta)^3\phi(k_p-k_f)}{k_p+(n-1)k_f-(1-\beta)^3\phi(k_p-k_f)}\right]$	n = (3/ψ) Al_2O_3/EG Cu/EG TiO_2/water Al_2O_3/water
	Chandrsekar et al. [33]	2009	$\frac{k_{eff}}{k_f}=\left[\frac{k_p+(n-1)k_f+(n-1)(1+\beta)^3\phi(k_p-k_f)}{k_p+(n-1)k_f-(1-\beta)^3\phi(k_p-k_f)}\right]$ $+\frac{c\varphi(T-T_0)}{\mu ka^4}$	CuO/water TiO_2/water n = 3 for spherical particles
	Duangthongsu and Wongwises [34]	2009	$\frac{k_{eff}}{k_f}=a+b\phi$ a = 1.0225, b = 0.0272 for T = 15 °C a = 1.0204, b = 0.0249 for T = 25 °C a = 1.0139, b = 0.0250 for T = 35 °C	TiO_2/water
	Patel *et al.* [35]	2010	$\frac{k_{eff}}{k_f}=\left(1+0.135\left(\frac{k_p}{k_f}\right)^{0.273}\phi^{0.467}\left(\frac{T}{20}\right)^{0.547}\left(\frac{100}{d_p}\right)^{0.234}\right)$	Oxide and metallic nanofluids
	Chandrasekar *et al.* [2]	2010	$\frac{k_{eff}}{k_f}=\left(\frac{C_{p.eff}}{C_{pf}}\right)^a\left(\frac{P_{eff}}{P_f}\right)^b\left(\frac{M_f}{M_{eff}}\right)^c$ a = -0.023, b = 1.358, c = 0.125	Al_2O_3/water
	Vajjha *et al.* [36]	2010	$\frac{k_{eff}}{k_f}=\frac{k_p+2k_f+2\phi(k_p-k_f)}{k_p+2k_f-\phi(k_p-k_f)}+5*10^{4\beta\rho_pC_p}$ $\sqrt{\frac{K_bT}{\rho_Pd}}f(T,\phi)$ $f(T,\phi)=(-3.0669*10^{-2}\phi-3.91123*10^{-3})+$ $(2.8217*10^{-2}\phi+3.917*10^{-3})\frac{T}{T_0}$	Al_2O_3 (60:40) EG/ water
	Corcione [37]	2011	$\frac{k_{eff}}{k_f}=1+4.4\,Re^{0.4}\,Pr^{0.66}\left(\frac{T}{T_{FR}}\right)^{10}\left(\frac{k_e}{k_f}\right)^{0.03}\phi^{0.66}$	Al_2O_3/water

2.2. Viscosity

Various models have been suggested to model the viscosity of a nanofluid mixture, that take into account the percentage of nanoparticles suspended in the base fluid.

Table 2 includes some data relevant to aluminum oxide (Al_2O_3), copper oxide (CuO) and titanium dioxide (TiO_2), dispersed in water picked from the literature.

Table 2. *Correlations on viscosity*

Model	Reference	Year	Correlation	Relevant information
Theoretical	Einstein [38]	1906	$\frac{\mu_{eff}}{\mu_f}=1+2.5\phi$	spherical particles
	Saito [39]	1950	$\frac{\mu_{eff}}{\mu_f}=\left(1+\frac{2.5}{(1-\varphi)}\varphi\right)$	spherical particles
	Brinkman [40]	1952	$\frac{\mu_{eff}}{\mu_f}=\frac{1}{(1-\phi)^{2.5}}$	spherical particles
	Lundgren [41]	1972	$\frac{\mu_{eff}}{\mu_f}=\frac{1}{1-2.5\phi}$	moderate concentration
	Batchelor [42]	1977	$\frac{\mu_{eff}}{\mu_f}=1+2.5\phi+6.2\phi^2$	spherical particles
Experimental	Wang *et al.* [43]	1999	$\frac{\mu_{eff}}{\mu_f}=1+7.3\varphi+123\varphi^2$	Al_2O_3/ water
	Tseng and Lin [44]	2003	$\frac{\mu_{eff}}{\mu_f}=13.47\exp(35.98\phi)$	Al_2O_3/EG TiO_2/water
	Maiga *et al.* [45]	2005	$\frac{\mu_{eff}}{\mu_f}=1+7.3\varphi+123\varphi^2$	Al_2O_3/water
	Koo and Kleinstreuer [46]	2005	$\mu_{Brownian}=5*10^4\beta\rho_f\phi$ $\sqrt{\frac{K_bT}{2\rho_P r_p}}\left[(-134.63+1722.3\phi)+(0.4705-6.04\phi)\frac{T}{T_0}\right]$ $\beta=\begin{cases}0.0137(100\phi)^{-0.8229} & \phi\le 0.01\\ 0.0011(100\phi)^{-0.7272} & \phi\ge 0.01\end{cases}$	CuO/water
	Kulkarni *et al.* [47]	2006	$\ln\mu_{eff}=-(2.8751+53548\phi-107.12\phi^2)+(1078.3+15857\phi+20587\phi^2)\left(\frac{1}{T}\right)$	CuO/water
	Buongiorno [30]	2006	$\frac{\mu_{eff}}{\mu_f}=1+5.45\phi+108.2\phi^2$ $\frac{\mu_{eff}}{\mu_f}=1+39.11\phi+533.9\phi^2$	TiO_2/water Al_2O_3/water
	Chen *et al.* [12]	2007	$\frac{\mu_{eff}}{\mu_f}=1+10.6\phi+112.36\phi^2$	TiO_2/EG
	Nguyen *et al.* [3]	2007	$\frac{\mu_{eff}}{\mu_f}=0.904\exp(0.1483\phi)$ for d_p = 47 nm $\frac{\mu_{eff}}{\mu_f}=1+0.025\phi+0.015\phi^2$ for d_p = 36 nm	Al_2O_3/water CuO/water

			$\frac{\mu_{eff}}{\mu_f} = 1.475 - 0.319\iota + 0.051\phi^2 + 0.009\phi^3$ for d_p = 29 nm	
	Namburu *et al.* [48]	2007	$Log(\mu_{eff}) = Ae^{-BT}$ $A = 1.8375\phi^2 - 29.643\phi + 165.56$ $B = 4 * 10^{-6}\phi^2 - 0.001\phi + 0.0186$	CuO/water
	Duangthongsu and Wongwises [34]	2009	$\frac{\mu_{eff}}{\mu_f} = a + b\phi + c\phi^2$ a = 1.0226, b = 0.0477, c = - 0.0112 for T = 15 °C a = 1.0130, b = 0.0920, c = - 0.0150 for T = 25 °C a = 1.0180, b = 0.1120, c = - 0.0177 for T = 35 °C	TiO_2/water
	Chandrasekar *et al.* [2]	2010	$\frac{\mu_{eff}}{\mu_f} = 1 + b\left(\frac{\varphi}{1-\varphi}\right)^n$; b = 1631, n = 2.8	Al_2O_3/water
	Vajjha [36]	2010	$\frac{\mu_{eff}}{\mu_f} = Ae^{C\varphi}$; A = 0.9197, C = 22.8539	CuO/water

3. Discussion

In this paper, an attempt has been made to cover most of the investigations performed on the thermal conductivity and viscosity of nanofluids available in the literature. It has been found that temperature, particle size and shape and volume fractions have significant effects over the viscosity and the thermal conductivity of nanofluids. Results indicate that viscosity increases as the particle volume fractions increase, and nanofluids behave in a Newtonian way for low particle volume concentrations. No existing model or correlation is capable of precise prediction of the viscosity enhancement with respect to volume fractions. Although there have been a few contradictory results in the field of temperature effect on viscosity, generally, researchers conclude that viscosity decreases with an increase of temperature. There are some correlations available for the temperature influence over viscosity; most of which are not versatile enough and a debate still exists about the particle size impact on viscosity.

To illustrate these uncertainties, three types of nanoparticles, Al_2O_3, CuO and TiO_2, were chosen because they have been widely studied in recent years as promising additives.

Accurate formulas for the thermophysical properties (density, viscosity, specific heat and thermal conductivity) are necessary for these nanofluids to perform a thermal and fluid dynamic analysis, so few correlations were selected.

Table 3. *Thermophysical properties of base fluid and nanoparticles at 293 K*

Property	**Base fluid (water)**	**Nanoparticle (Al_2O_3)**	**Nanoparticle (CuO)**	**Nanoparticle (TiO_2)**
specific heat (J/kg K)	4179	773	551	692
density (kg/m^3)	997.1	3960	6000	4230
thermal conductivity (W/m·K)	0.613	40	33	8.4
viscosity (kg/ms)	8.91×10^{-4}	-	-	-

Further on, Figure 1 presents several selected models on thermal conductivity.

One can notice that almost all correlations give an increase in thermal conductivity, excepting the Li and Peterson [29] correlation for alumina nanofluid that goes to a decrease of thermal conductivity when adding nanoparticles. Even so, the thermal conductivity is increasing to almost 25% by adding nanoparticles to water.

In regard to viscosity, Figure 2 contains the plotting of some correlations in connection with the particle volume fraction. Figure 2 a. plots some theoretical correlations available in the open literature and one can see the increase in viscosity with volume fraction, going to an overall increase of about 15% for a 5% volume fraction.

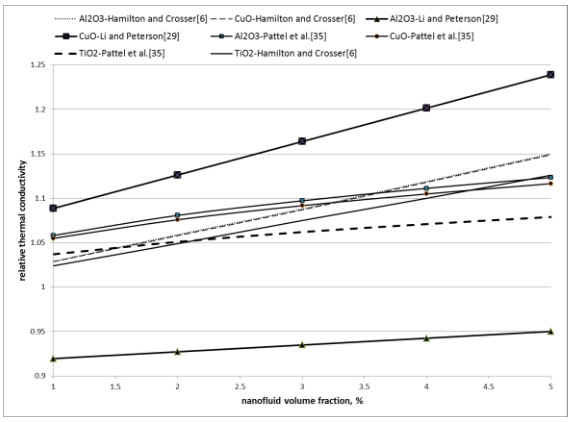
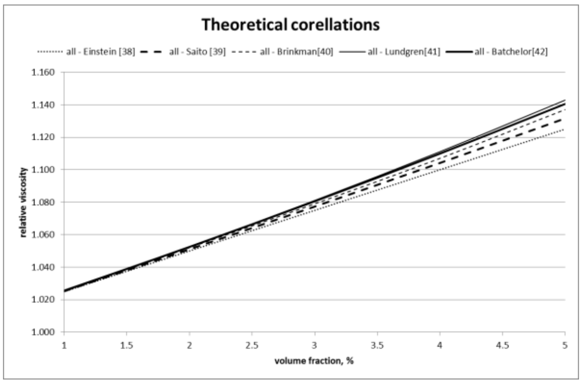
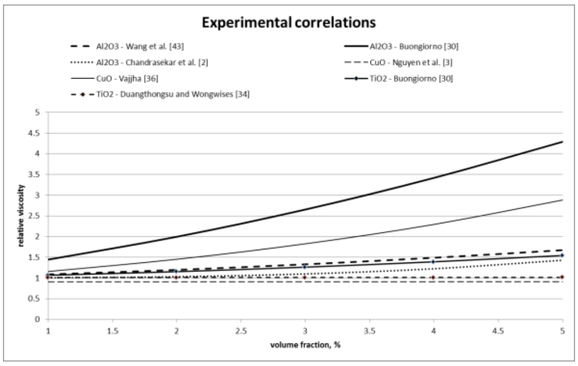


Fig. 1. *Relative thermal conductivity for selected nanofluids*

Figure 2 b shows the variation of viscosity for considered nanofluids in regard to some experimental correlations available in the open literature. It can be noticed that the highest increase was obtained for alumina-water nanofluid that goes to 400 % increase using Buongiorno [30] experimental formulae.



a.



b.

Fig. 2. *Relative viscosity for selected nanofluids:*
a. theoretical correlations;
b. experimental correlations

Looking at Tables 1 and 2, one can notice that a lot of correlations are depending exclusively on particle volume fraction and eventually on temperature variations and this leads to the same thermal conductivity and viscosity enhancement regardless of nanoparticle material. Table 3 presents these correlations. Moreover, all theoretical models for viscosity prediction do consider only the particle volume fraction variation.

Table 4 is a review on viscosity and thermal conductivity enhancement for the considered nanofluids. One can notice that the results are highly dependent on each author research and their nanofluid method of approach. These results highly recommend a better approach to the theory of nanofluids and further work in this area.

Table 3. *Correlations depending only on particle volume fraction*

Model	Reference	Year	Correlation	Relevant information
THERMAL CONDUCTIVITY				
Theoretical	Hamilton and Crosser [6]	1962	$\frac{k_{eff}}{k_f} = 4.97\varphi^2 + 2.72\varphi + 1$	$k_p / k_f > 100$
	Lu and Lin [26]	1996	$\frac{k_{eff}}{k_f} = 1 + a\phi + b\phi^2$	For k = 10: a = 2.25, b = 2.27 For k = ∞ a = 3.00, b = 4.51

Experimental	Li and Peterson [29]	2006	$\frac{k_{eff}-k_f}{k_f}=0.764\phi+0.0187(T-273.15)-0.462$	Al_2O_3/water
			$\frac{k_{eff}-k_f}{k_f}=3.761\phi+0.0179(T-273.15)-0.307$	CuO/water
	Buongiorno [30]	2006	$\frac{k_{eff}}{k_f}=1+2.92\phi-11.99\phi$	TiO_2/water
	Timofeeva *et al.* [31]	2007	$k_{eff}=(1+3\phi)k_f$	Al_2O_3/water
	Duangthongsu and Wongwises [34]	2009	$\frac{k_{eff}}{k_f}=a+b\phi$ a = 1.0225, b = 0.0272 for T = 15 °C a = 1.0204, b = 0.0249 for T = 25 °C a = 1.0139, b = 0.0250 for T = 35 °C	TiO_2/water
VISCOSITY				
Theoretical	Einstein [38]	1906	$\frac{\mu_{eff}}{\mu_f}=1+2.5\phi$	spherical particles
	Saito [39]	1950	$\frac{\mu_{eff}}{\mu_f}=\left(1+\frac{2.5}{(1-\varphi)}\varphi\right)$	spherical particles
	Brinkman [40]	1952	$\frac{\mu_{eff}}{\mu_f}=\frac{1}{(1-\phi)^{2.5}}$	spherical particles
	Lundgren [41]	1972	$\frac{\mu_{eff}}{\mu_f}=\frac{1}{1-2.5\phi}$	moderate concentration
	Batchelor [42]	1977	$\frac{\mu_{eff}}{\mu_f}=1+2.5\phi+6.2\phi^2$	spherical particles
Experimental	Wang *et al.* [43]	1999	$\frac{\mu_{eff}}{\mu_f}=1+7.3\varphi+123\varphi^2$	Al_2O_3/water
	Tseng and Lin [44]	2003	$\frac{\mu_{eff}}{\mu_f}=13.47\exp(35.98\phi)$	Al_2O_3/EG TiO_2/water
	Maiga *et al.* [45]	2005	$\frac{\mu_{eff}}{\mu_f}=1+7.3\varphi+123\varphi^2$	Al_2O_3/water
	Kulkarni *et al.* [47]	2006	$\ln\mu_{eff}=-\left(2.8751+53548\phi-107.12\phi^2\right)+\left(1078.3+15857\phi+20587\phi^2\right)\left(\frac{1}{T}\right)$	CuO/water
	Buongiorno [30]	2006	$\frac{\mu_{eff}}{\mu_f}=1+5.45\phi+108.2\phi^2$ $\frac{\mu_{eff}}{\mu_f}=1+39.11\phi+533.9\phi^2$	TiO_2/water Al_2O_3/water
	Chen *et al.* [12]	2007	$\frac{\mu_{eff}}{\mu_f}=1+10.6\phi+112.36\phi^2$	TiO_2/EG
	Nguyen *et al.* [3]	2007	$\frac{\mu_{eff}}{\mu_f}=0.904\exp(0.1483\phi)$ for d_p = 47 nm	Al_2O_3/water CuO/water

			$\frac{\mu_{eff}}{\mu_f} = 1 + 0.025\phi + 0.015\phi^2$ for d_p = 36 nm $\frac{\mu_{eff}}{\mu_f} = 1.475 - 0.319\iota + 0.051\phi^2 + 0.009\phi^3$ for d_p = 29 nm	
	Namburu *et al.* [48]	2007	$Log(\mu_{eff}) = Ae^{-BT}$ $A = 1.8375\phi^2 - 29.643\phi + 165.56$ $B = 4 * 10^{-6}\phi^2 - 0.001\phi + 0.0186$	CuO/water
	Duangthongsu and Wongwises [34]	2009	$\frac{\mu_{eff}}{\mu_f} = a + b\phi + c\phi^2$ a = 1.0226, b = 0.0477, c = - 0.0112 for T = 15 °C a = 1.0130, b = 0.0920, c = - 0.0150 for T = 25 °C a = 1.0180, b = 0.1120, c = - 0.0177 for T = 35 °C	TiO_2/water
	Chandrasekar *et al.* [2]	2010	$\frac{\mu_{eff}}{\mu_f} = 1 + b\left(\frac{\varphi}{1-\varphi}\right)^n$; b = 1631, n = 2.8	Al_2O_3/water
	Vajjha [36]	2010	$\frac{\mu_{eff}}{\mu_f} = Ae^{C\varphi}$; A = 0.9197, C = 22.8539	CuO/water

Table 4. *Viscosity and thermal conductivity enhancement*

Nanofluid/correlation	***Nanofluid volume concentration, %***				
	1	**2**	**3**	**4**	**5**
VISCOSITY					
Al_2O_3 - Wang *et al.* [43]	8.53	19.52	32.97	48.88	67.25
Al_2O_3 - Buongiorno [30]	44.45	99.58	165.38	241.86	329.03
Al_2O_3 - Chandrasekar *et al.* [2]	0.42	3.02	9.67	22.28	42.85
CuO - Nguyen *et al.* [3]	-9.47	-9.33	-9.20	-9.06	-8.93
CuO - Vajjha [36]	15.58	45.26	82.56	129.43	188.34
TiO_2 - Tseng and Lin [44]	1828.57	2661.24	3853.42	5560.32	8004.18
TiO_2 - Buongiorno [30]	6.53	15.23	26.09	39.11	54.30
TiO_2 - Duangthongsu and Wongwises [34]	1.09	1.18	1.27	1.36	1.45
all - Einstein [38]	2.50	5.00	7.50	10.00	12.50
all - Saito [39]	2.53	5.10	7.73	10.42	13.16
all - Brinkman [40]	2.50	5.20	7.90	10.70	13.70
all - Lundgren [41]	2.56	5.26	8.11	11.11	14.29
all - Batchelor [42]	2.56	5.25	8.06	10.99	14.05
THERMAL CONDUCTIVITY					
Al_2O_3 - Hamilton and Crosser [6]	2.89	5.90	8.80	11.90	15.00
CuO-Hamilton and Crosser [6]	2.87	5.80	8.70	11.80	14.90
TiO_2-Hamilton and Crosser [6]	2.40	4.90	7.50	10.00	12.60

Al_2O_3-Li and Peterson [29]	-8.04	-7.27	-6.51	-5.74	-4.98
CuO-Li and Peterson [29]	8.86	12.62	16.38	20.14	23.91
Al_2O_3-Pattel *et al.* [35]	5.82	8.08	9.72	11.12	12.34
CuO-Pattel *et al.* [35]	5.49	7.59	9.17	10.49	11.65
TiO_2-Pattel *et al.* [35]	3.70	5.10	6.20	7.10	7.90

4. New challenge: hybrid nanofluids?

In spite of some inconsistency in the reported results and insufficient understanding of the mechanism of the heat transfer in nanofluids, it has emerged as a promising heat transfer fluid.

In the continuation of nanofluids research, the researchers have also tried to use hybrid nanofluids recently, which is engineered by suspending dissimilar nanoparticles either in mixture or composite form.

The idea of using hybrid nanofluids is to further improvement of heat transfer and pressure drop characteristics by trade-off between advantages and disadvantages of individual suspension, attributed to good aspect ratio, better thermal network and synergistic effect of nanomaterials.

The introduction of a new concept of combined/hybrid nanofluids will be clearly explained in this article. Furthermore, this very short review summarizes recent research on thermophysical properties, heat transfer and possible applications and challenges of hybrid nanofluids. Review showed that proper hybridization may make the hybrid nanofluids very promising for heat transfer enhancement; however, many research works are still needed in the fields of preparation and stability, characterization and applications to overcome the challenges.

Some research started in 2007, but their number slowly increases over the years, as one can see from Figure 3.

Moreover, Tables 5 and 6 are a summary of recent experimental results obtained in the area of hybrid nanofluids, in connection with thermophysical properties.

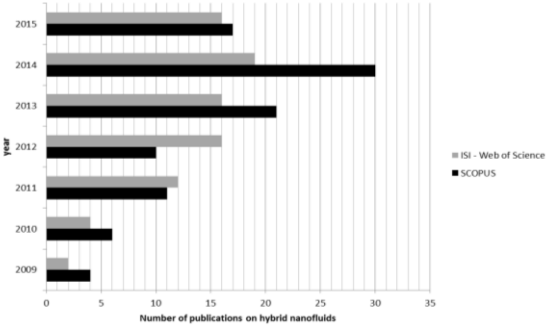


Figure 3. *Number of publications on hybrid nanofluids*

Table 5. *Investigations on density, heat capacity and viscosity of hybrid nanofluids*

Investigators	Nanofluids	Properties and important findings
Ho *et al.* [49]	Al_2O_3 - MEPCM/ water	Density and heat capacity: temperature independent measurement, classical correlations are applicable.
Ho *et al.* [49]	Al_2O_3 - MEPCM/ water	Viscosity: drastically increase of the effective dynamic viscosity of the hybrid suspension.
Suresh *et al.* [50]	Al_2O_3 - Cu/water	Viscosity: viscosity increases substantially higher than the increase in thermal conductivity.
Botha *et al.* [51]	Ag - Silica/oil	Viscosity: the nanofluid showed Newtonian behavior at lower silica concentrations and followed the Bingham flow model at high concentrations.
Baghbanzadeh *et al.* [52]	Silica/MWCNT water	Density and viscosity: at high concentration, better influence compared to mono nanofluids.

Table 6. *Investigations on thermal conductivity of hybrid nanofluids*

Investigators	Nanofluids	Important findings
Ho *et al.* [49]	Al_2O_3 - MEPCM/water	Significant enhancement of thermal conductivity of PCM suspension with Al_2O_3 nanoparticle dispersion relative to pure water.
Suresh *et al.* [50]	Al_2O_3 - Cu/water	A very significant enhancement in the effective thermal conductivity due to hybridization of alumina nanoparticles using metallic copper particles.

Botha *et al.* [51]	Ag - silica/oil	The theoretical increase in thermal conductivity is much lower than that observed.
Paul *et al.* [53]	Al-Zn/ethylene glycol	A maximum 16% thermal conductivity enhancement at 0.1 vol% particle concentration was achieved.
Baghbanzadeh *et al.* [54]	Silica/MWCNT	Thermal conductivity in case of hybrid nanofluids is between enhancement of MWCNT sand silica nanofluids.
Abbasi *et al.* [55]	γ-Al_2O_3/MWCNT	Enhancement of the thermal conductivity of hybrid nanofluids can reach up to 14.75 % at a volume fraction of 0.01.
Nine *et al.* [56]	Al_2O_3 - MWCNT/water	Thermal conductivity better with non-ground MWCNT s compared to ground MWCNTs.
Munkhbayar *et al.* [57]	Ag-MWCNT/water	Improved dispersion of CNT sinthematrix, as well as the decoration of the MWCNT s with silver may be the reason for enhancement in thermal conductivity.
Aravind *et al.* [58, 59]	Graphene-MWNT/water	High thermal transport characteristics of grapheme–MWNT composite nanofluids is attributed to the high aspect ratio of MWNT and graphene.
Chen *et al.* [60]	Fe_2O_3 - MWNT/ water	Significant enhancement of thermal conductivity due to synergistic effect.
Batmunkh *et al.* [61]	Ag - TiO_2/water	Thermal conductivity TiO_2/water nanofluid was enhanced by addition of Ag particle.

As one can see from Table 5 and Table 6, all the studies are encouraging in recommending hybrid nanofluids as new heat transfer fluids. Anyway, more experimental work is needed in order to attain a good stability for these new fluids.

5. Conclusions

Recently, important theoretical and experimental research works on convective heat transfer appeared in the open literature on the enhancement of heat transfer using suspensions of nanometer-sized solid particle materials, metallic or metallic oxides in base heat transfer fluids. Thus, this paper presents an overview of the recent investigations in the study the thermophysical characteristics of nanofluids.

General correlations for the effective thermal conductivity and viscosity of nanofluids are presented. Compared to the reported studies on thermal conductivity, investigations on viscosity of nanofluids are limited. Most of the experimental and numerical studies showed that nanofluids exhibit enhanced thermophysical properties compared to their base fluids, which increase significantly with increasing concentration of nanoparticles as well as Reynolds number.

Also, hybrid nanofluids containing composite nanoparticles yield significant enhancement of thermal conductivity. However, the long-term stability, production process, selection of suitable nanomaterials combination to get synergistic effect and the cost of nanofluids may be major challenges behind the practical applications.

Further theoretical and experimental research investigations on the effective thermal conductivity and viscosity are needed to demonstrate the potential of nanofluids and to understand their heat transfer characteristics, as well as to identify new and unique applications for these fields.

Nomenclature

c_p - specific heat, J/kg °C;
h - heat transfer coefficient, W/m^2 °C;
k - thermal conductivity, W/m °C;
n - shape factor;
Pr - Prandtl number;
Re - Reynolds number;
T - temperature, °C;
φ - volume concentration, %;
μ - viscosity, kg/ms;
ρ - density, kg/m^3;
Subscripts
eff - effective, refers to nanofluid effective property;
f - fluid;
p - particle.

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