Jurnal Teknologi

Full Paper

CONSIDERATION OF CARBON NANOTUBE-BASED NANOFLUID IN THERMAL TRANSFER.

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Article history
Article history
Received
1 January 2016
Received in revised form
18 May 2016
Accepted
15 June 2016

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Abstract

In the current trend towards demand for effective heat removal of high density heat flux, research into nanofluids have escalated due to the rise in thermal conductivity associated with the coolants. Are nanofluids a solution for a better thermal management? Does the application of nanofluids as coolants have limitations? This article presents a review of the thermophysical properties of carbon nanotube-water nanofluids, in particular the desired properties of low viscosity and high thermal conductivity. The effects of the concentration, temperature, aspect ratio, and surfactant on the thermal conductivity and viscosity of carbon nanotube nanofluid have been studied experimentally. These effects are thendiscussed for evaluation of the applicability of carbon nanotube-based nanofluidas a coolant for heat removal purposes.

Keywords: Nanofluid; viscosity; conductivity

Abstrak

Dalam keadaan trend semasa terhadap permintaan keatas penyingkiran fluks haba berketumpatan tinggi yang lebih berkesan, penyelidikan tentang bahan penyejuk *nanofluids* telah meningkat disebabkan oleh pertambahan kekonduksian terma yang dikaitkan dengan bahan tersebut. Adakah *nanofluids* suatu penyelesaian untuk pengurusan terma yang lebih baik? Adakah aplikasi *nanofluids* sebagai bahan penyejuk mempunyai limitasi? Kertas kerja ini membentangkan kajian *review* sifat-sifat termofizikal karbon nanotiub-air *nanofluids*, khususnya sifat-sifat kelikatan yang rendah dan kekonduksian haba yang tinggi. Kesan kepekatan, suhu, nisbah aspek, dan *surfactant* keatas keberaliran haba dan kelikatan karbon nanotiub *nanofluids* telah dikaji melalui beberapa siri ekperimen. Kesan-kesan kemudiannya dibincang untuk dinilai kesesuaian aplikasi kabon nanotiub *nanofluids* sebagai bahan penyeuk bagi tujuan penyingkiran haba.

Kata kunci: *Nanofluid*; kelikatan; kekonduksian

1.0 INTRODUCTION

Nanotechnology involving nanofluids as coolants has become the emerging technology in the current century, revolutionizing our cooling systems. Colloids made of suspension of Nano metric size particles in base fluids have been of great interest to researchers due to their unique thermal properties. The rise in thermal conductivity associated with these nanofluids appeal to the heating and cooling industries with increasing demand for effective coolants to transfer heat from increasingly smaller components and systems. The colloidal solutions are often made through the dispersion of nanoparticles with very high conductivity into liquids. This increases the mixture's effective thermal conductivity, much higher than that

of the original base fluid.However, researches have shown that enhancement of the thermal conductivity and increased in the heat transfer performance only occurs at some low concentrations of the nano-sized particles. Convection between the solid-fluid interfaces is augmented due to the large surface area to volume ratio of the nanoparticles. At high concentrations, clogging and sedimentation occur. The extent of heat transfer enhancement as the nanoparticles concentration increases and the effects of the presence of surfactants added to reduce clogging and agglomeration, have yet to be fully investigated and understood. These issues must be addressed for nanofluids to be established in practical applications.

Classification of the nanoparticles are generally according to their shapes; (i) spherical nanoparticles (copper, Cu; iron, Fe; gold, silver, Ag; aluminium oxide, Al2O3; copper oxide, CuO; titanium oxide, TiO2; etc.), or (ii) nanotubes (carbon nanotubes, CNT). This paper presents the study of carbon nanotube-based nanofluids with the base fluids being water, oil or water-ethylene glycol. The single-walled carbon nanotube (SWCNT) may consist of a single graphene layer folded on itself and the multi-walled carbon nanotube (MWCNT) consists of a coil of several layers of graphene. This class of nanoparticles is characterized by its large aspect ratio. The diameter and length of the CNT is of the order of nanoscale and microscale respectively.With these magnitudes, the thermal conductivity for the SWCNT can be as high as 6000 W/mKwhile for the MWCNT up to 3000W/mK. The suspension of the CNT is usually accomplished by applying a high frequency acoustic energy (ultra sound), chemically, and mechanically mixed. A necessary ingredient, a surfactant is generally added to homogenize the distribution of the CNT in the base fluid and stabilize the suspension [1]. Surfactants most often used are Sodium Dodecylbenzenesulphonate (SDBS), gum Arabic GA, hexadecyltrimethylammonium bromide or cetrimonium bromide (CTAB). The conventional density and specific heat relationships used currently seem satisfactory and this has been the practice. Although there have been multiple reports on studies of nanoparticles nanofluids, few are available on the CNT nanofluids. Here, the details of the studies completed on the thermal conductivity and viscosity of CNT-based nanofluids are explained. Discussions with reference to available models and experimental data are also presented.

Table 1:Thermal conductivity and viscosity models on nanofluids

Thermal conductivity	**Model**
$\frac{\lambda_{nf}}{\lambda_{fb}} = \frac{\lambda_{np} + 2\lambda_{fb} - 2\varphi_v(\lambda_{fb} - \lambda_{np})}{\lambda_{np} + 2\lambda_{fb} + 2\varphi_v(\lambda_{fb} - \lambda_{np})}$	Maxwell (1881)
$\varphi_v\left(\frac{\lambda_{np} - \lambda_{nf}}{\lambda_{np} + 2\lambda_{nf}}\right) + (1-\varphi_v)\left(\frac{\lambda_{fb} - \lambda_{nf}}{\lambda_{fb} + 2\lambda_{nf}}\right) = 0$	Bruggeman
$\frac{\lambda_{nf}}{\lambda_{fb}} = \frac{\lambda_{np} + (n-1)\lambda_{fb} - (n-1)(\lambda_{fb} - \lambda_{np})\varphi_v}{\lambda_{np} + (n-1)\lambda_{fb} + (n-1)(\lambda_{fb} - \lambda_{np})\varphi_v}$	Hamilton-Crosser
$\lambda_{nf} = \lambda_{statique} + \lambda_{brownien}$ $\lambda_{statique} = \lambda_{bf}\frac{\lambda_{np} + 2\lambda_{fb} - 2\varphi_v(\lambda_{fb} - \lambda_{np})}{\lambda_{np} + 2\lambda_{fb} + 2\varphi_v(\lambda_{fb} - \lambda_{np})}$ $\lambda_{brownien} = \frac{\kappa_B T}{3\pi\mu_{fb} d_{np}}$	Koo et Kleinstreuer
$\frac{\lambda_{nf}}{\lambda_{fb}} = \frac{\lambda_{np} + 2\lambda_{bf} - 2(\lambda_{fb} - \lambda_{np})(1+\beta)^3\varphi_v}{\lambda_{np} + 2\lambda_{fb} + 2(\lambda_{fb} - \lambda_{np})(1+\beta)^3\varphi_v}$	Yu et Choi
$\lambda_{nf} = \lambda_{fb}\left[1 + \frac{\lambda_{np}\left(\frac{2\varphi_v(r_{np} + l_{np})}{r_{np} l_{np}}\right)}{\lambda_{fb}\left(\frac{3(1-\varphi_v)}{r_{fb}}\right)}\right] + \frac{C\varphi_v(T - T_0)}{r_{np}^2 l_{np}^2 \mu_{fb}}\ln\left(\frac{l_{np}}{d_{np}}\right)$	Walvekar
Viscosity	**Model**

$\mu_{nf} = \mu_{fb}(1+2.5\varphi_v)$	Einstein:
$\mu_{nf} = \mu_{fb}\frac{1}{(1-\varphi_v)^{2.5}}$	Brinkman
$\mu_{nf} = \mu_{fb}(1+\eta\varphi_v + k_H{\varphi_v}^2 + ...)$	Batchelor
$\mu_{nf} = \mu_{fb}(1+\eta\varphi_v)\ \eta = \frac{0.312r_a}{\ln 2r_a - 1.5} + 2 - \frac{0.5}{\ln 2r_a - 1.5} - \frac{1.872}{r_a}$	Brenner
$\mu_{nf} = \mu_{fb}\left(1-\frac{\varphi_v}{\varphi_M}\right)^{-\eta\varphi_M}$	Krieger et Dougherty
$\mu_{nf} = \mu_{fb}\left(1-\frac{\varphi_v}{\varphi_M}\right)^{-2}$	Maron& Pierce (1956)

2.0 ANALYSIS

2.1 Theoretical Models on Thermal Conductivity

Table 1 lists the most commonly used models in the study of nanofluids. Among these, the Maxwell [2] model is generally satisfactory for suspensions containing spherical particles of relatively low solid concentrations. The model, however, ignores the effects of the particle shape or size. The Bruggeman model too, does not consider the shape and size of the particles. The model that does consider the geometry of the nanoparticles, a geometric factor called sphericity, is the Hamilton-Crosser model [3].The model, however,is applicable when the thermal conductivity of the nanoparticles is at least 100 times higher than that of the base fluid. The model proposed by Koo and Kleinstreuer [4] consists of two terms; the first, relates the static term to the Maxwell model, and the second, relates the static term to the Brownian motion. Among these models, the model of Hamilton-Crosser has been favored in past experimental results. Unfortunately, it appears that this model is unable to reproduce the development of thermal conductivity of CNT-based nanofluids[5]. Meanwhile, the model of Yu and Choi [6] considers the effect of interface between the particles and the base fluid. Amore comprehensive model is that developed by Walvekar*et al.* [7],it takes into account many parameters including the shape, the aspect ratio, the thermal conductivity of the CNT and the base fluid, as well as the Brownian motion effects.

2.2 Experimental Studies on Thermal Conductivity

A compilation of experimental results of thermal conductivity of CNT-based nanofluids have been done by Wang et al. [8].Their results show an improvement of the thermal conductivity of the nanofluids compared to that of the base fluid depending on the volume fraction concentration. Besides, results show a great dispersion of the experimental values of thermal conductivity [9].

In the large majority of existing work, it has been established that the thermal conductivity of the nanofluids increases with temperature [10, 11]. The aspect ratio, the average length to the average diameter, and shape can also have a significant influence on the thermal conductivity of NTC-based nanofluids [12]. According to Yang *et al.* [13] the increase in the thermal conductivity is based on the aspect ratio that varies from 20 to 200%. Wusiman*et al.* [14] showed that the use of the surfactant SDBS can have a rather negative effect on the thermal conductivity. Paritosh*et al.* [15] have experimentally studied the effects of the mechanical and ultrasonic mixing on the thermal performance of a CNT-water nanofluid. Deterioration of the thermal conductivity of nanofluidshas been found to generally occur as a result of clustering and sedimentation [16].

2.3 Theoretical Models on Viscosity

Numerous studies, theoretical as well as experimental, have been conducted to evaluate the nanofluid dynamic viscosity and quantify the importance of the main parameters affecting it [17, 18]. In this paper, the usual models of nanofluids listed in Table 1 will be looked into. Further details are available in the works of Mahbubul and Amalina [19]. For very dilute suspensions of spherical particles of less than 1%, the Einstein formula is considered adequate [20]. The model, however, neglects the effects of particle size and the inter-particle interactions. This shortcoming is fulfilled by the Brinkman [21] model of up to a concentration of less than 4% by volume. For particle concentrations of up to less than 10 % the Batchelor model [22] is found to be satisfactory. For higher volume fractions, the Krieger and Dougherty model may be used instead [23]. Maron and Pierce (Table 1) offer a simplified model developed by Krieger and Dougherty and this model remains the most frequently used model to date. Meanwhile, the Brener model (Table 1) does integrate the particle

shape and some studies have indicated that the model works for low shear rates.

2.4 Experimental Studies on Viscosity

Experiments by Phuoc*et al.* [24] have shown that the dynamic viscosity of the CNT nanofluids increases with the volume concentration. The MWCNT-water nanofluid tested showed rheofluidifiant behaviour at low shear rate becoming Newtonian at high shear rates for mass concentrations of 0.1% and 0.5%. Previous studies have shown that the dynamic viscosity of the nanofluids decreases as the temperature increases [17, 25]. However, there is a cut-off temperature beyond which the dynamic viscosity increases with temperature as discovered by Nguyen *et al.* [26]. Several studies have indicated that the addition of a surfactant - to prevent agglomeration - usually results in an increase in the dynamic viscosity [27]. A study by *Chen et al.* [28] indicated a sharp decline in the dynamic viscosity of a nanofluid composed of MWCNT dispersed in silicone oil with a Hexamethyldisiloxane (HMDS) surfactant. *Garg et. al.* [29] studied the effects of ultrasonic blending time, cluster size and the aspect ratio of the CNT, on viscosity. The presence of the agglomerates, the time-dependent shear thinning property (thixotropic behaviour), and the method used for synthesizing are some of the factors that may have affected the dynamic viscosity and rheological behaviour of the CNY-based nanofluids [17, 30]. There seems to be much inconsistency between the theory and experimental studies reported. It is imperative that these issues are resolved before any blanket statement is made on any specific application of the nanofluids.

2.5 Heat Transfer

Some previous work has confirmed that the addition of the CNT is advantageous with a relatively improved performance [31]. Table 2 presents different results of heat transfer gain reported in the literature.

Table 2 Heat transfer gain reported

Reference	Flow	Nanofluid used	Gain
[32]	Laminar	MWCNT/water (φ_v=0.5%)	350%
[15]	Laminar	MWCNT/water (φ_m=1%)	32%
[33]	Laminar	MWCNT/water +EG (φ_v=0.45%)	160%
[34]	Laminar	MWCNT/water (φ_v=0.015%)	7%
[31]	Laminar	MWCNT/water (φ_m=1%)	50%
[35]	Laminar	CNT/water (φ_m=4%)	250%
[36]	Laminar	MWCNT/ water (φ_m=0.25%)	33%
	turbulent		40%

As in the case with viscosity, there exist a disparity between the results reported. Thus, contrary to the statements made by enthusiasts of nanofluids, in the absence of reliable and consistent theoretical relations, the thermo-physical properties of CNT-based nanofluids should be assessed in advance and experimentally in order to choose the best suitable nanofluid.

3.0 RESULTS AND DISCUSSION

In this work, four types of nanofluids containing the multi-walled carbon nanotubes (MWCNT) have been investigated. Table 3 summarizes the composition and the properties of the different nanofluids investigated.

Table 3 Properties of the different nanofluids tested

Nanofluid/Type (NTC)	Ratio	Base fluid	Surfactant
N1/NC7000	160	Distilled water	SDBS
N2/NC7000	160	Distilled water	Lignine (L)
N3/NC7000	160	Distilled water	Polycarboxylat sodium (O)
N4/CNTA	90	Distilled water	Polycarboxylat sodium (O)

3.1 Effects of Concentration

Figure 1(a) shows the development of the apparent viscosity of the N1 nanofluid depending on the volume fraction at 20°C. Figure 1b shows the evolution of the viscosity for different temperatures and for a high shear rate. It can be seen that the apparent viscosity increases with the volume fraction of the CNT beyond 0.055%, a hike from that at 0.418% to 0.55%. The nanofluid follows the Newtonian behavior for volume fractions of less than a critical value of 0.055%, in the range of the shear rate studied. Beyond this concentration, the fluid seems to follow a rheofluidifiant behavior which is even more pronounced than that at the high volume fraction. Finally, the evolution of the apparent dynamic viscosity with the volume fraction of the CNT is similar regardless of the operating temperature.

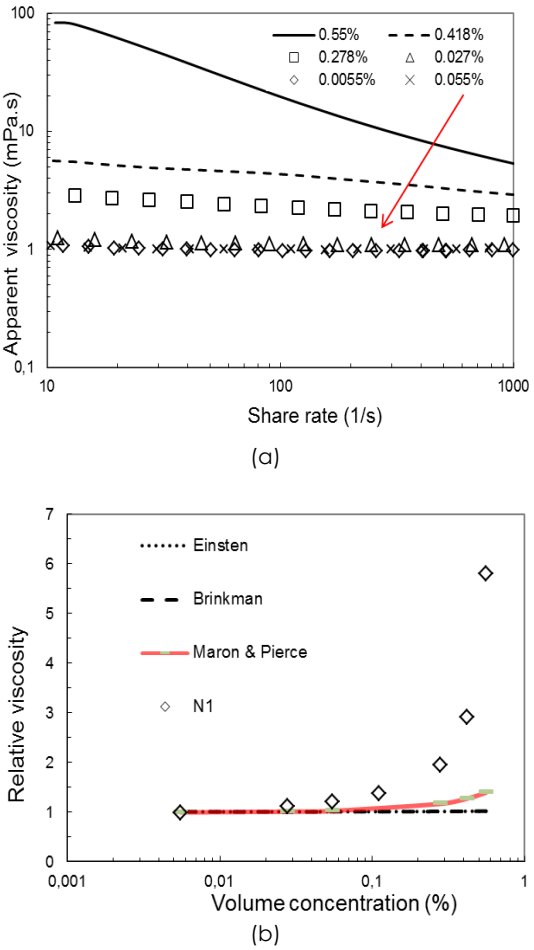


Figure 1 Viscosity versus; (a) shear rate at 20°C for different concentration ; (b) concentration for different models.

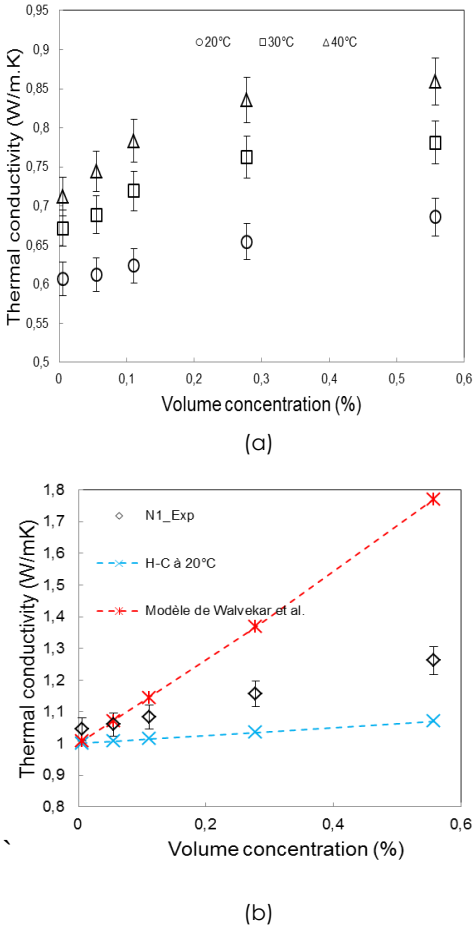


Figure 2 Evolution of conductivity against concentration; (a)for three temperatures, (b) comparison with model at *T*= 20°C.

Figure 1(b), shows that for concentrations under 0.05%, the fluid viscosity is close to that of water and the temperature has no significant effect on viscosity. There is a gap between the evolution of experimental relative viscosity and that predicted by the models of Eistein, Brinkmann, and Maron-Pierce (Table 1)for high volume fractions, beyond 0.05% in the experiment completed. This difference is attributed to the presence of aggregates that have not been taken into account by the models. The Einstein and Brinkman models clearly fail to predict the viscosity of the CNT nanofluids for concentration that is higher than 0.05%. These models did not reproduce the experimental data as seen here in Figure 1 (b). The Maron and Pierce model too, fails but at a slightly higher volume fraction i.e. 0.1%.

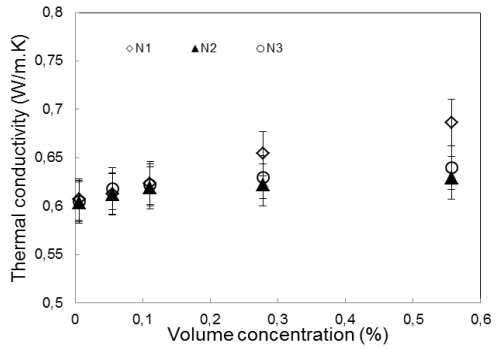
Figure 2(a) shows the evolution of thermal conductivity against concentration for three temperatures; 20°C, 30°C, and 40°C. Figure 2b shows the evolution of thermal conductivity against concentration, and a comparison with the Hamilton-Crosser (H-C) and Walvekar models (Table 1) and at *T*= 20°C.

The results from Figure 2(a) clearly show that the thermal conductivity of the nanofluidconsistently increases with the volume of the CNT fractions and temperature. This increase is the same for the low volume fraction (less than 0.111%). The same developments have been found with the other three types of nanofluids. This is the desired outcomes much commended by researches involved in nanofluids; as operating temperatures of heat exchanging devices increases, the thermal conductivity of nanofluids increases manifolds.

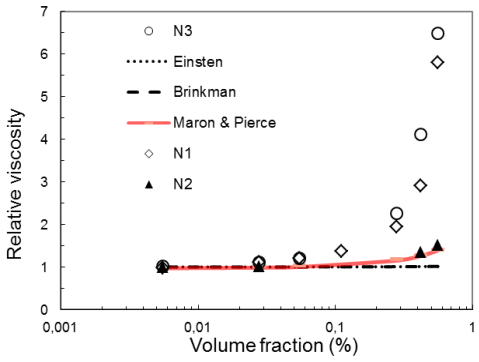
There is a wide gap between the experimental data and the Hamilton-Crosser and Walvekar*et al.*models. For the latter, this difference increases significantly with the volume fraction of the CNT with a maximum deviation of approximately 18%. Results show that the model of Walvekar (Table 1) largely overestimates the evolution of the relative thermal conductivity of the CNT nanofluid, particularly for particle concentrations exceeding 0.055%. For concentrations below 0.055%, this model is in good agreement with the experimental data.

3.2 Effect of the Type of Surfactant (N1 ;N2 ; N3)

Nanofluids N1, N2, and N3 investigated here consist of the same nanotubes nanofluids but with different surfactantsadded (Table 3). The development of the thermal conductivity of thenanofluidsN1, N2, and N3 at 20°C as a function of volume fraction is shown in Figure 3(a). Figure 3(b) shows the viscosity as a function of the volume fraction at 20°C for these nanofluids.



(a)



(b)

Figure 3(a) Evolution of the thermal conductivity versus volume fraction; (b) Evolution of viscosity versus the volume fraction

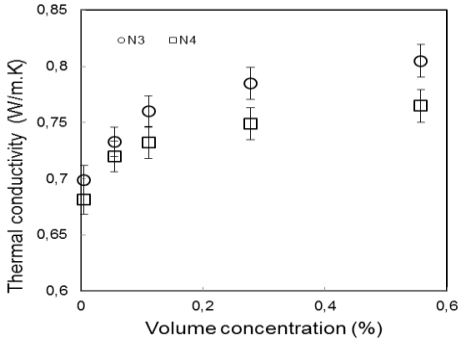
Figure 3(a) shows that the gap between the curves of the evolutions of the thermal conductivities of the three nanofluids is relatively insignificant (less than 3.5%) over the range of concentrations studied. This confirms that the type of surfactant used has no significant effect on the thermal conductivity, up to 0.6% volume concentration, before significant differences couldpossibly appear.

It is worthy to note the importance of the impact of the agglomerates and the choice of the primordial surfactant. The surfactants can affect the overall thermophysical properties and thus conclusions made on the properties must be studied carefully. In this case, the lignin surfactant is best suited compared to the SDBS and polycarboxylat sodium (O). However at low concentrations, the type of surfactant used has no significant effect.

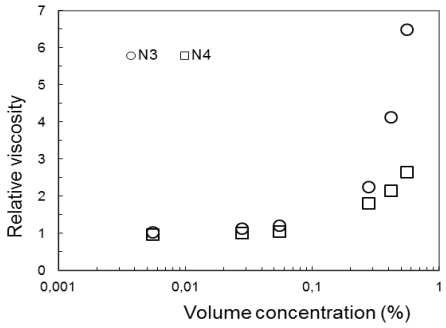
3.3 Effect of the Aspect Ratio

Figures 4(a) and 4(b) show the development of the conductivity and viscosity of nanofluids N3 and N4 depending on the concentration for the two different aspect ratios.

The gap between the curves of the thermal conductivities of nanofluids N3 and N4 is less than 3.5%, which shows that the effect of the aspect ratio can be considered negligible at 20°C. There is still a slight increase of conductivity based on the aspect ratio.



(a)



(b)

Figure 4 For two different aspect ratios; (a) Evolution of the conductivity against concentration, (b) Evolution of the viscosity against concentration

Similarly, for low volume concentration (< 0.05%) there is no impact of the form factor and at higher concentrations, the greater the aspect ratio the higher the viscosity.

4.0 CONCLUSION

Characterization of the thermo-physical properties of NTC based nanofluids studied allow us to highlight the influence of the volume fraction, the temperature, the type of surfactant and the aspect ratio of the CNT. Results show that at low concentrations of less than 0.055% volume, it is observed that:

- The rheological behavior of the nanofluids is Newtonian regardless of the applied shear rate and

it is independent of the type of surfactant and the aspect ratio.
- The temperature does not have a significant effect on the evolution of the relative viscosity.
- The dynamic viscosities of the nanofluids are close to those of the related base fluids.
- Temperature had a significant effect on the improvement of the thermal conductivity and this improvement is more pronounced at low concentrations.

For these reasons, the nanofluidfor the thermal transfer must be within low concentration (depending on surfactant) to limit the viscosity issue. Volume fraction under 0.025% can increase the conductivity of up to 10%. The review completed has shown that the thermophysical properties may deviate under certain conditions. Thus, cautiously, the performance should be verified with experimentally obtained data where possible to realize the practicality and rational behind models used.

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