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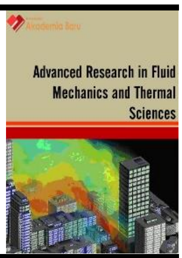

Thermal Conductivity and Dynamic Viscosity of Nanofluids: A Review

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ABSTRACT

Thermal conductivity is one of the rheology properties that vital for engineering fluid which indispensable for heat transfer enhancement. For this reason, nanofluid is getting wider attention nowadays due to the presence of nanoparticles in the base fluid can further improve thermal conductivity and dynamic viscosity. These are two important properties for new engineering fluid in providing better cooling and lubricating effects, especially in mechanical and tribology applications. In this paper, specifically, nanofluids thermal conductivity and dynamic viscosity are discussed comprehensively. Both properties' thermal conductivity and viscosity of nanofluids are improved over the base fluid. Furthermore, these two properties increase when more volume concentrations of nanoparticles are added. In addition, the thermal conductivity also improved with increasing the temperature. From the literature review, the maximum enhancement of thermal conductivity for single nanofluid is recorded 36% of MWCNTs in distilled water. On the other hand, the maximum enhancement of viscosity is recorded 39% of Al2O3 in water-ethylene glycol over base fluid. The hybrid nanofluids that consist of more than one type of nanoparticles exhibit better thermal conductivity where the maximum enhancement is recorded 68% of Cu-TiO2 in deionized water. For dynamic viscosity measurement, the maximum enhancement of hybrid nanofluids is recorded 168% of MgO-MWCNT in ethylene glycol. Therefore, to sum up, hybrid nanofluids are really promising to enhance heat transfer performance especially for heating and cooling applications. The potential of these nanofluids should be explored extensively to discover its advantages over conventional working fluid.

Keywords:
Thermal conductivity; dynamic viscosity; nanofluids; heat transfer; enhancement

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1. Introduction

Driven by green technology and long-term manufacturing sustainability, nanofluids are introduced as an alternative to the conventional fluid. Nanofluids are engineered colloidal suspension for minimizing environmental effects as well as for enhancing working fluid thermal and rheology properties. This is an innovative approach for new generation working fluid. Lubrication plays a vital role in the mechanical component's movement as it can reduce the friction and subsequently reduce mechanical forces. It has been reported that lubrication was found 4000 years ago in Egypt based on a large statue of a man pouring a kind of liquid [1]. Conventional liquids possess limited thermal conductivity, environmental pollution and worker's health issues that needs to resolve. Therefore, in the last 20 years ago the efforts have been devoted to coming up with the solution. Since then, a single nanofluid was introduced by the researchers and hybrid nanofluid also presented for the first time in 2015. The term "Nanofluid" was first introduced by Choi in 1995 [2]. Nanofluid by definition is referred as a working fluid that contains colloidal mixture of metallic or non-metallic nanomaterial with the particle size less than 100nm [3]. Research on nanoparticles has been increased rapidly by employing different types of nanosized materials with different volume concentrations particularly for various applications such as machining, heat exchanger, radiator, refrigerator, air-conditioner and electronics cooling. In recent years, nanofluids are prepared using different types of nanoparticles such as Al_2O_3, ZnO, TiO_2, CNT, SiO_2 and ZrO_2. These materials can be considered inexpensive and yet demonstrate better thermal-physical properties. The thermal properties or convective heat transfer coefficient of base oil can further be enhanced using nanomaterials mainly due to the thermal transport capability of each particle. The performance of nanofluid in carrying heat from the heat source depends on its thermal conductivity, specific heat, viscosity and density [4]. Besides, the nanoparticle's shape also significantly influences the thermal conductivity and dynamic viscosity of the fluid [5]. According to Pryazhnikov *et al.,* [6] there is a direct proportional relationship between particle size and thermal conductivity. The thermal conductivity of nanofluid is improved remarkably when the thermal conductivity of the base fluid is lower. The solid heat transfer performance is better compared with the liquid heat transfer performance. This is attributed to the mass molecule motion when nanofluid is circulating throughout the system which resulting in higher thermal conductivity enhancement of nanofluids.

The volume percentage or weight percentage of nanoparticles dispersed in based-oil is between 0.25% and 5% for nanofluids preparation. It has been reported that the presence of SWCNTs dispersed in the base coolant can increase the thermal conductivity of up to 105% at 1 vol% of nanoparticle [7]. Thus, the heat is transferred more effectively from the cutting zone and subsequently the temperature can be reduced outstandingly. Fotowat *et al.,* [8] discovered that about 17% of thermal conductivity enhancement of nanofluids over a base fluid. However, there was a corrosion effect in Aluminium and Copper however, it was negligible in Stainless Steel when all these materials were submerged in the Al_2O_3 nanofluid. Rashmi *et al.,* [9] also studied the effects of corrosion using carbon wall nanotube nanofluids and various base fluids. On the other hand, nanofluid viscosity increases with increasing of nanoparticle diameter size and volume concentration however, decreases drastically in increasing temperature [10]. Murshed and Estelle [11] suggested that the study of nanofluid viscosity should also consider pH value, nanoparticle size and shape as the published articles are limited. According to Nabil *et al.,* [12], more research is needed to understand the behavior of nanofluid including its characteristics and suitability in engineering applications. Therefore, in this paper, specifically, nanofluids thermal conductivity and dynamic viscosity are discussed comprehensively. The objective is to explore and expand the knowledge of nanofluids in terms of preparation, thermal-physical behavior and its modeling as well as application potential in the near future.

2. Base Fluid

Base fluid or single-phase liquid exhibits low thermal conductivity in which the effectiveness of heat transfer could not be obtained. This is the reason that researchers have attempted to enhance thermal-physical properties by introducing second-phase liquid such as single and hybrid nanofluid. The selection of base fluid is vital in preparing nanofluids in order to obtain nanofluids stability and enhancing its thermal-physical properties. There are many types of base fluid that are commonly used nowadays to prepare nanofluids such as water, deionized water, ethylene glycol (EG), vegetable oil, a mixture of water and ethylene, etc. Each of these base fluids has its own advantages. For instance, Ethylene Glycol is commonly used as anti-freeze addictive due to it able to further reduce the freezing temperature of working liquid (0°C to -12°C) for circulating the liquid particularly in heating and cooling systems [13]. Nazari *et al.,* [14] revealed that a 30% volume of Ethylene Glycol in the nanofluids has better cooling performance than 50% volume of Ethylene Glycol. It was recommended by Lim *et al.,* [15] to mix water and ethylene glycol of 60:40 ratios as the base fluid for cooling purposes. The vegetable oil-based fluid is one of many alternative lubricants that can be considered as base fluid due to some reasons. For example, Wang *et al.,* [16] revealed that palm oil has better lubrication properties compared to other vegetable oils. Commonly known for biodegradability and low production cost, it also has good lubrication properties [17]. Furthermore, it has great potential as metal cutting liquid which needs to be explored [18]. Synthetic or mineral oils display good lubrication properties; however, they possess lower thermal properties which not suitable for the metal cutting process that generates high temperature at the cutting zone especially under high-speed machining [17]. According to Xuan and Li [19], oil-based nanofluid was better than water-based nanofluid in terms of heat transfer characteristics. Minh *et al.,* [20] mentioned that based on comprehensive studies emulsion 5% coolant was more effective than soybean oil in enhancing hard milling performance in terms of surface roughness, cutting forces and the tool life.

2.1 Nanomaterial

The characteristics of nanomaterials depend on their size, shape, physical properties and dispersibility. The nanoparticles can be divided into three groups which are based on its physical characteristics such as (i) Metallic particles like Fe, Al, Cu, Au, Ag, (ii) Non-metallic or metal carbide particles like Al_2O_3, CuO, SiC, TiO_2 and (iii) Carbon Nanotubes [21]. The size of the particle should be less than 100nm to be considered as a nanoparticle. The effectiveness of lubricating properties depends on the smaller size of nanoparticle which can form a protective film layer and subsequently reduce the friction between the cutting tool and workpiece during the machining process. Nanomaterials have a high ratio of surface area over their weight and possess anti-friction properties in base fluids [22]. According to Zhang *et al.,* [23], MoS_2 nanoparticles show good lubrication performance, while CNTs were able to increase the heat transfer coefficient. By dispersing both nanomaterials into a base fluid, it would enhance the thermo-physical properties of nanofluid. Similarly, findings by Wang *et al.,* [24] Al_2O_3, MoS_2, and SiO_2 have better lubricating properties when grinding Nickel Alloy GH4169. It has been reported that Fe_3O_4 nanoparticles exhibited the maximum thermal conductivity enhancement of 200% in water [25]. Vafaei *et al.,* [26] revealed that the maximum enhancement of thermal conductivity of 48% was associated with Fe_3O_4 nanoparticles. Similarly, the maximum enhancement of the nanofluid viscosity was found almost 294% when Fe_3O_4

nanoparticles dispersed in ethylene glycol-water mixture [27]. Li *et al.,* [28] evaluated the grinding performance of six different nanofluids (MoS_2, ZrO_2, CNT, polycrystalline diamond, Al_2O_3, and SiO_2) and found that CNT nanofluids produced excellent thermal properties compared with other nanofluids. According to Guo *et al.,* [29], carbon nanotubes have outstanding characteristics compared to other nanomaterials in terms of chemical stability, physical strength, high electrical and thermal conductivity, as well as mechanical resistance. Raju *et al.,* [30] mentioned that multiwall carbon nanotubes (MWCNT) nanoparticles have a maximum thermal conductivity of 3000 W/mK compared with other nanomaterials resulting in 36% improvement of thermal conductivity on nanofluid compared to the conventional fluid. Moreover, this type of nanomaterial easily disperses in distilled water when sodium dodecyl sulfate (SDS) is added [31]. Copper metallic nanoparticles demonstrate 95% higher thermal conductivity at 400 W/mK compared to Copper Oxide (CuO) which was at 20 W/mK [32]. Furthermore, Aluminum oxide (Al_2O_3) nanoparticles display better thermo-physical properties compared to SiO_2 and TiO_2 nanofluids for the same volume concentrations whereas Al_2O_3 have lower lubrication properties [17,33]. Minh *et al.,* [20] claimed that Al_2O_3 nanoparticles produced excellent tribological and anti-toxic properties. While Su *et al.,* [34] mentioned that graphite nanoparticles were able to reduce anti-friction characteristics where a physical deposition layer could form on the surface thereby resulting in low friction forces. Sayuti *et al.,* [35] revealed that the Vickers hardness of silicon dioxide (SiO_2) nanoparticle is 1000kgfmm-2 which possesses good mechanical properties of hard and brittle particles.

2.2 Single and Hybrid Nanofluids

Single nanofluid is referred as a one-type nanoparticle with a certain amount of concentration dispersing into the base fluid. Single nanofluid has been received great attention since 1995 with the objective to enhance base fluid and conventional working fluid properties and subsequently improve cooling and lubricating characteristics. Yogeswaran *et al.,* [36] applied TiO_2-Ethylene Glycol nanofluid for enhancing milling performance. Esfe *et al.,* [37] evaluated MgO/water nanofluid thermal conductivity coefficient between 0.01 and 0.03 volume fractions. In order to further enhancing the thermal-physical and rheology properties of single nanofluids, a combination of different nanoparticles dispersing into the base fluid could be the solution. Therefore, for the past few years, research on hybrid nanofluids has attracted great attention to exploring its potential. Hybrid nanofluids possess excellent thermal and rheology properties due to synergistic effect and can be prepared by two methods: (i) suspending two or more different nanoparticles in the base fluid, (ii) combining between two or more nanoparticles physically in the base fluid which is referred as hybrid material [38]. For instance, MgO-MWCNTs in EG, Al_2O_3-SiC, MoS2-CNT in Synthetic Lipids and Al_2O_3-GNP in oil-water emulsion were the hybrid nanofluids prepared in various applications [17,23,26,39]. This hybrid material exhibits better thermophysical properties due to the synergistic effect which does not exist in the single nanofluids. Many scholars mentioned that hybrid nanoparticles that disseminate in the base fluid produced higher heat transfer enhancement, cooling effect and anti-friction performance rather than single nanoparticles in the material cutting process [21,23,39]. The combination of two different nanoparticles for preparing the hybrid nanofluids could produce manifesting results that able to increase heat transfer effectiveness in many engineering applications. In such, there are applications of hybrid nanofluids in heat exchanger, car radiator, rubbing process, electronics component cooling system, machining process as well as in solar energy collector [41-45]. However, the research of hybrid nanofluids for improving machining performance especially in metal cutting process are still limited, therefore more experimental work needs to be conducted in order to explore its great potential [17,46]. Both lubricating and cooling effects can be offered by hybrid nanofluids which regards the formation of thin-film on the contact interface to alleviate the cutting forces and able to demonstrate higher thermal-rheology properties that can carry the heat away from the heat source. Due to the advantages far outweigh the disadvantages, thus, the potential of hybrid nanofluid and its application in the metal cutting process is promising in the future and should be explored extensively.

3. Thermal Conductivity of Nanofluids

Heat can be transferred through conduction, convection and radiation. In these modes of heat transfer, the heat flows from high to low temperatures. Thermal conductivity is defined as the heat transfer rate within the temperature difference through a thickness material per unit area [47]. Thus, thermal conductivity can be described as the ability of a material to transfer the heat by conduction through it. This thermal property is critical for nanofluid to carry and dissipate the heat effectively. Subsequently, the cooling rate could be faster and the operating system would be more reliable. It essential that thermal conductivity measurement should be conducted for a new introduction of nanofluid which the objective is to discover the capability of the liquid to carry and dissipate the heat. In order to measure nanofluids thermal conductivity, thermal properties analyzer such as KD2 Pro and TC3010 can be used [14,29,49-52]. It is essential to ensure that nanofluid is stable and no particle sedimentation found when measuring thermal conductivity. Basically, the thermal conductivity can be measured by applying three different techniques; i) The transient hot-wire method, ii) Temperature oscillation method and iii) 3-ω method. The main factor affecting the thermal conductivity of nanofluid is volume concentration [48,49]. Besides, the nanoparticle size, shape, type of base fluid, temperature and preparation technique also will influence the thermal conductivity. The enhancement of nanofluid thermal conductivity depends on volume concentration and working temperature. Higher thermal conductivity of nanofluid observed at higher volume concentration and temperature as reported by Alirezaie *et al.,* [50]. However, the thermal conductivity decreased with the increase in the percentage of Ethylene Glycol in the mixture of Ethylene Glycol/water as a base fluid [51]. Furthermore, the thermal conductivity of oil-based nanofluid decreases at the temperature greater than 180°C due to the vaporization of organic oil which regards its flash point [52]. Abubakar *et al.,* [53] stated that 0.08% of temperature reduction at 0.8% volume fraction of Fe_3O_4 in water over the pure water in microchannel heat sinks thermal analysis.

In addition, certain nanoparticles such as MWCNTs and Ag possess higher thermal conductivity compared to other nanoparticles. Therefore, the dispersion of these nanoparticles would significantly enhance the thermal conductivity of nanofluids over base fluid. However, obtaining the stability of these nanofluids is always challenging which is associated with the higher density. In order to avoid instability conditions of suspension, nanoparticles concentration should be managed wisely as they have significant influence on the thermal conductivity and stability. On the other hand, the effect of nanoparticle shape is significant for nanofluid thermal conductivity. For instance, as reported by Jeong *et al.,* [54] that nearly rectangular ZnO exhibited 18% of thermal conductivity enhancement over the sphere shape of the same material which recorded 15% enhancement at the same concentration of 5.0vol%. This is due to a higher interface area which directly increasing surface interaction and the possibility of higher contact area with other materials in transferring the heat [55,56]. According to Cui *et al.,* [57], nanofluids that consist of the cylindrical shapes of nanoparticles displays higher thermal conductivity rather than sphere shape due to micro-convection activities of rotational motion in nanofluids. However, Kim *et al.,* [58] mentioned that the thermal conductivity of nanofluids increases with decreasing nanoparticles size. With smaller particle sizes, the suspension would be more stable and the chemical interaction could happen even in confine space.

Nevertheless, according to Jeong *et al.,* [54], the nanoparticle shape is more dominant in getting higher thermal conductivity of nanofluids than the particle size which regards specifically to ZnO and more study should be conducted for other nanoparticles. The summary of thermal conductivity and viscosity enhancement findings for single and hybrid nanofluid are shown in Table 1 and Table 2 respectively.

Table 1
Summary of single nanofluid thermal conductivity and viscosity maximum enhancement

Author	Base Fluid	Nano-particles	Volume Fraction	Measurement Temperature	Measurement Property	Maximum Enhancement (%)
Sundar *et al.,* [59]	Ethylene Glycol (EG): Water 20:80% 40:60% 80:20%	Al_2O_3	0.0%, 0.3%, 0.6%, 0.8%, 1.0%, 1.5%	20°C – 60°C	Thermal Conductivity Dynamic Viscosity	32.26% of 1.5 vol% at 60°C 1.37 times compared to base fluid
Chen *et al.,* [60]	Natural Seawater	SiC	0.0% - 1.0%	10°C – 50°C	Thermal Conductivity	5.2%
Huminic *et al.,* [61]	Distilled Water	SiC	0.5 wt%, 1.0 wt%	20°C – 50°C	Thermal conductivity Dynamic Viscosity	17.62% of 1.0 wt% at 50C 17.62%
Al-Waeli *et al.,* [62]	Deionized water	SiC	1% - 4%	25°C – 60°C	Thermal Conductivity	8.2%
Yu *et al.,* [63]	Ethylene Glycol (EG)	ZnO	0% - 5%	10°C – 60°C	Thermal Conductivity	26.5% of 5 vol%
Suganthi and Rajan [64]	Water	ZnO	0.25% - 2%	35°C – 55°C	Dynamic Viscosity	28%
Nadooshan [65]	Ethylene Glycol (EG)	ZnO	0.125% - 4.0%	20°C – 50°C	Thermal Conductivity	20% of 4 vol.%
Lim *et al.,* [15]	Water-Ethylene glycol (EG)	Al_2O_3	0.2%, 0.4%, 0.6%, 0.8%, 1%	15°C – 55°C	Thermal Conductivity Dynamic Viscosity Convective Heat Transfer Coefficient	10% of 1 vol% 39% of 1 vol% 25.4% of 1 vol%
Andhare and Raju [66]	Distilled Water	MWCNTs	0.2%	33°C,40°C,50°C	Thermal Conductivity Contact Angle	36% reduced by 33.3%
Murshed *et al.,* [67]	De-ionized Water	TiO_2	0.001% - 0.05%	10°C – 60°C	Thermal Conductivity	17%
Najiha *et al.,* [68]	De-ionized Water	TiO_2	0.5%,2.5%,4.5%	30°C – 60°C	Thermal Conductivity	11.4%
Nazari *et al.,* [14]	Water	Al_2O_3 CNT	0.1%, 0.25%, 0.5%	20°C – 50°C	Heat Transfer Coefficient Heat Transfer Coefficient	6% of 0.5vol.% 13% of 0.25vol.%
Xuan and Li *et al.,* [19]	Water	Cu	2wt% - 9wt%	15°C – 55°C	Thermal Conductivity	1.78 times higher than base fluid
Baghbanzadeh *et al.,* [69]	Distilled Water	MWCNTs	0 wt.% - 1 wt.%	27°C, 40°C	Thermal Conductivity	23.3%

Ilyas *et al.,* [70]	Thermal Oil (THO)	MWCNTs	0 wt.% - 1 wt.%	25°C - 60°C	Thermal Conductivity	28.7% of 1wt.%
Li *et al.,* [71]	Waste Cooking Oil	SiC	0.02% - 0.1%	25°C - 60°C	Thermal Conductivity	23%
Khedkar *et al.,* [72]	Paraffin Oil	Fe_3O_4	0.01% - 0.1%	27°C	Thermal Conductivity	20%
Abareshi *et al.,* [73]	Deionized Water	Fe_3O_4	0% - 3%	10°C - 40°C	Thermal Conductivity	11.5% of 3 vol.% at 40°C

Table 2
Summary of hybrid nanofluid thermal conductivity and viscosity maximum enhancement

Author	Base Fluid	Nanoparticles	Volume Fraction	Measurement Temperature	Measurement Property	Max. Enhancement (%)
Toghraie *et al.,* [74]	Ethylene glycol (EG)	$ZnO - TiO_2$	0% - 3.5%	25°C – 50°C	Thermal Conductivity	32% of 3.5 vol% when measured at 50°C
Afrand *et al.,* [75]	Engine Oil (SAE40)	SiO_2 - MWCNTs	0.0625%, 0.125%, 0.25%, 0.5%, 0.75%,1.0%	25°C – 60°C	Dynamic Viscosity	37.4%
Harandi *et al.,* [76]	Ethylene glycol (EG)	MWCNTs-Fe_3O_4	0.1%, 0.25%, 0.45%, 0.8%, 1.25%, 1.8%, 2.3%	25°C – 50°C	Thermal Conductivity	30% of 2.3 vol% when measured at 50°C
Madhesh *et al.,* [77]	De-ionized water	$Cu - TiO_2$	0.1% - 2.0%	30°C – 90°C	Heat Transfer Coefficient	68%
Mechiri *et al.,* [78]	Vegetable Oils (Ground nut)	Cu - Zn	0.1%,0.3%, 0.5%	30°C – 60°C	Thermal Conductivity	1.125-times
Akilu *et al.,* [79]	Ethylene glycol (EG)	TiO_2 - CuO/C	0.5% - 2.0%	30°C – 60°C	Thermal Conductivity	16.7%
					Dynamic Viscosity	80%
Esfe *et al.,* [80]	Ethylene glycol (EG)	SWCNT- MgO	0.0% - 2.0%	30°C – 50°C	Thermal Conductivity	32% of 2 vol.%
Aberoumand and Jafarimoghaddam [81]	Transformer Oil	Ag - WO_3	1 wt.%, 2 wt.%, 4 wt.%	40°C – 100°C	Thermal Conductivity	41%
Kannaiyan *et al.,* [82]	Water-Ethylene glycol (EG)	Al_2O_3 - CuO	0.05%, 0.1%, 0.2%	20°C – 70°C	Thermal Conductivity	45%
Afrand [83]	Ethylene glycol (EG)	MgO - FMWCNTs	0% - 0.6%	25°C – 50°C	Thermal Conductivity	21.3%
Nabil *et al.,* [84]	Water-Ethylene glycol (EG)	$TiO_2 - SiO_2$	0.5% - 3.0%	30°C – 80°C	Thermal Conductivity	22.8%
					Dynamic Viscosity	62.5%
Sundar *et al.,* [85]	Distilled Water	GO - Co_3O_4	0.05%, 0.1%, 0.15%, 0.2%	20°C – 60°C	Thermal Conductivity	19.14%
					Dynamic Viscosity	1.70-times
	Ethylene glycol (EG)				Thermal Conductivity	11.85%
					Dynamic Viscosity	1.42-times

Wei *et al.,* [86]	Diathermic Oil	SiC – TiO_2	0.1% - 1.0%	10°C – 50°C	Thermal Conductivity	8.39%
Sundar *et al.,* [87]	Water-Ethylene glycol (EG)	ND - Co_3O_4	0% - 0.15%	20°C – 60°C	Thermal Conductivity	16.0% at 60°C
					Dynamic Viscosity	1.51-times at 60°C
Yarmand *et al.,* [88]	Distilled Water	GNP - Pt	0.0% - 0.1%	20°C – 40°C	Thermal Conductivity	17.77% of 0.1 vol.% at 40°C
					Dynamic Viscosity	33% of 0,1% at 40°C
Soltani and Akbari [89]	Ethylene glycol (EG)	MgO - MWCNT	0.1% - 1.0%	30°C – 60°C	Dynamic Viscosity	168%
Sundar *et al.,* [90]	Water-Ethylene glycol (EG)	ND – Fe_3O_4	0.005%, 0.1%, 0.2%	20°C – 60°C	Thermal Conductivity	17.8%
					Dynamic Viscosity	2.19-times

Table 1 and Table 2 show the important findings of nanofluids thermal conductivity and dynamic viscosity. It has summarized the maximum enhancement based on experimental studies. The maximum enhancement of thermal conductivity for single nanofluid is 36% of MWCNTs in distilled water. Meanwhile, the enhancement of viscosity for single nanofluid is recorded 39% of Al_2O_3 in water-EG over the base fluid. On the other hand, the hybrid nanofluids exhibit superior thermal conductivity over single nanofluid where the maximum enhancement is recorded 68% of Cu-TiO_2 in deionized water. Furthermore, the maximum enhancement percentage for hybrid nanofluid viscosity is recorded 168% of MgO-MWCNT in ethylene glycol. Based on experimental results, hybrid nanofluids have greater potential as the future working fluid in cooling and heating which regards the enhancement of thermal-physical properties of single nanofluids.

3.1 Thermal Conductivity Model

The overall cost of experiments nowadays is getting more expensive and conducting the experiments may consume a lot of time. Hence, the prediction correlation models of nanofluid thermal conductivity developed by scholars may assist in calculating the important property such as thermal conductivity. Table 3 shows thermal conductivity models developed by scholars based on actual experimental data. The regression models may differ due to different considerations of nanoparticle characteristics such as size, shape, different materials and coating layer as well as the type of the base fluid and its composition when preparing the fluid. However, the results obtained using the correlation model should be verified with the actual experimental data.

Table 3
Summary of nanofluids thermal conductivity models developed by various scholars

Author	Thermal Conductivity Models	Description

Maxwell [91]	$$\frac{k_{nf}}{k}=\frac{k_s+2k+2\varphi(k_s-k)}{ks_s+2k-\varphi(k_s-k)}$$	The first model and always referred to define the effective thermal conductivity of combination liquid and solid suspensions. Where φ is the particle sphericity.
Hamilton and Crosser [92]	$$\frac{k_{nf}}{k}=\frac{k_s+(n-1)k+(n-1)\varphi(k_s-k)}{ks_s+(n-1)k-\varphi(k_s-k)}$$	This model considers a non-spherical nanoparticle and a shape factor that affects the liquid-solid thermal conductivity. Where n is the empirical shape factor given by 3/ ϕ and φ is the particle sphericity where 1 for the spherical and 0.5 for the cylindrical shape respectively.
Yu and Choi [93]	$$k_{pe}=\frac{[2(1-\gamma)+(1+\beta)^3(1+2\gamma)]\gamma}{-(1-\gamma)+(1+\beta)^3+(1+2\gamma)}k_p$$ $$\frac{k_{nf}}{k_f}=\frac{k_{pe}+2k_b+2(k_{pe}-k_p)(1+\beta)^3\emptyset}{k_{pe}+2k_b-(k_{pe}-k_b)(1+\beta)^3\emptyset}$$	The nanolayers at solid/liquid interface take into considerations when defining the equivalent thermal conductivity kpe. Where γ is the ratio of nanolayer thermal conductivity to particle thermal conductivity ($\gamma = k_{pe}/k$). In extreme case, $k_{pe} = k$, thus, γ is equivalent to 1. Where ϕ is the particle volume concentration and β is the ratio of thickness layer, h over particle radius, r ($\beta = h / r$).
Bruggeman [94]	$$\frac{k_{nf}}{k_{bf}}=\frac{1}{4}(3\emptyset-1)k_{np}+\left[(2-3\emptyset)k_{bf}\right]+\frac{k_{bf}}{4}\sqrt{\Delta}$$ where, $$\Delta=[(3\emptyset-1)^2\left(\frac{k_{np}}{k_{bf}}\right)^2+[(2-3\emptyset)^2+2(2+9\emptyset-9\emptyset^2)]\frac{k_{np}}{k_{bf}}]$$	Bruggeman has proposed a better model than two models above to predict the thermal conductivity at any v/v% and valid for spherical shape nanoparticle. Where ϕ is the particle volume concentration, k_{np} is the thermal conductivity of nanoparticle and k_{bf} is the thermal conductivity of the base fluid.
Feng *et al.*, [109]	$$\frac{k_s}{k_f}=\frac{k_p+2k_f-2\varphi(1+\lambda_{nano})^3(k_f-k_p)}{k_p+2k_f+\varphi(1+\lambda_{nano})^3(k_f-k_p)}$$	A model that considered of nanolayer, λ_{nano} which is referred to the ratio of nanoparticle thickness and radius $\left(\lambda_{nano}=\frac{t_p}{r_p}\right)$ in determining the nanofluid thermal conductivity.
Timofeeva *et al.*, [95]	$$\frac{k_{eff}}{k_f}=(1+3\phi)$$	The model considers geometry, agglomeration state and surface resistance of nanoparticles in determining the efficiency of thermal conductivity. k_{eff} is an effective thermal conductivity. Where ϕ is the particle volume concentration.
Vafaei *et al.*, [26]	$$\frac{k_{nf}}{k_{bf}}=0.9787+\exp(0.3081\phi^{0.3097}-0.002T)$$	The model is based on optimum conditions using an artificial neural network and can be used to predict hybrid nanofluids. Where ϕ is the particle volume concentration and T is measured temperature.

3.2 Dynamic Viscosity of Nanofluids

Viscosity is a measure of the liquid tendency against the flow. It is important rheology property of nanofluid that affecting the convective heat transfer coefficient [96]. When the liquid viscosity is constant over the shear rate, thus the liquid can be classified as Newtonian fluid as reported by Ghasemi and Karimipour [97]. On the other hand, when the fluid viscosity is changing over the shear rate, then the fluid is classified as Non-Newtonian fluid [98]. The viscometer is a key measurement instrument to measure the nanofluid viscosity. In order to measure nanofluids' dynamic viscosity, viscometer such as NDJ-9s rotating viscometer and Brookfield can be used [49,52-55]. For nanofluids, volume concentration is the most important factor whether it can be classified as Newtonian or Non-Newtonian fluid. For instance, Hong *et al.,* [99] found that FeO_4/water nanofluid exhibited Newtonian at a low concentration but behave non-Newtonian at a higher volume concentration due to the viscosity is changing over shear rate. The viscosity level in nanofluid is crucial because it may lead to high-pressure drop and subsequently more energy is required for pumping power prior to supply the cutting fluid. Based on the experimental investigation done by Pak and Cho [100], there was no significant influence on fluid viscosity based on different pH values and there was an additional 31% of the pumping penalty at a 3% of volume concentration where the fluid velocity remains constant.

However, nanofluid with higher viscosity has better performance for the lubricating effect due to it has a better contact area between the cutting tooltip and the workpiece [101,102]. This led to wettability effects of nanofluids on the contact surface. Moreover, higher viscosity prevents nanofluid from flowing freely out of the contact zone. This relationship between cutting fluid viscosity and surface tension is associated with cutting fluid wetting and spray characteristics. Sundar *et al.,* [21] reported out that the viscosity of nanofluids is directly proportional to volume concentration. In contrast, the viscosity is inversely proportional to the temperature. Brownian motion effect where the molecules move freely and randomly could be attributed to the inverse relationship between temperature and viscosity [103].

3.3 Viscosity Model

Besides the thermal conductivity model, scholars since the 1950s have developed a viscosity model for predicting working fluid viscosity based on experimental works as can be seen in Table 4. This is an attempted to model the important property of nanofluids by mathematical regressions. Hence, the property can be calculated from the mathematical modelling.

Table 4
Summary of nanofluids dynamic viscosity models developed by various scholars

Author	Viscosity Models	Description

Pak and Cho [100]	$\mu_{eff} = \mu_{eff}(1 + 39.11\phi + 533.9\phi^2)$	This model is referred to as two different metallic particles at room temperature. Where ϕ is the particle volume concentration.
Einstein [104]	$\mu_{eff} = \mu(1 + 2.5\phi)\ ,\ \phi \lesssim 0.05$	Based on the suspension of spherical particles. Where ϕ is the particle volume concentration.
Roscoe [105]	$\mu_{eff} = \mu_f(1 - \frac{\phi}{\phi_m})^{-2.5}$	A model for equal size rigid spheres and for all concentrations. Where ϕ is the particle volume concentration.
Koo and Kleinstreuer [106]	$\mu_{Brownian} = 5x10^4 \beta \rho m \phi_p \sqrt{\frac{K_g T}{2\rho_p r_p}[(-13463 + 17223\phi_p) + (0.4705 - 6.04\phi_p)T}$	Small scale interaction may occur between the hot and cold regions. Thus, temperature, particle size and volume fraction also affect the viscosity. Where ϕ is the particle volume concentration, *T* is temperature, ρ is particle density and *r* is particle radius.
Brinkman [107]	$\frac{\mu_{eff}}{\mu_f} = \frac{1}{(1 - \phi)^{2.5}}$	This model is extended from Einstein's model which dilutes copper, gold, CNT suspension. The model includes base fluid, nanoparticle viscosity and volume fraction respectively. Where ϕ is the particle volume concentration.
Batchelor [108]	$\mu_{eff} = 1 + 2.5\phi + 6.5\phi^2$	The effect of Brownian motion takes into consideration and it was extended from Einstein's model. Where ϕ is the particle volume concentration.

The suitability of the models as shown in Table 3 and Table 4 is relied more on the type of base fluid, size of the nanoparticle, type of nanoparticle, volume concentration and addition of surfactant. Moreover, the accuracy of these models had been tested which close to the experimental results. However, these thermal-physical modelling can be expanded by considering additional factors such as measured temperature, coated and uncoated particles and different shapes when more than one nanoparticle is dispersed in the base fluid. However, the experimental works must be performed in the sense that a deviation of the results can be avoided. Therefore, a newly developed regression model can be examined proven by conducting an experimental study to ensure the models and the results are valid. Recently, many researchers have developed empirical correlation models using different methods like genetic algorithms and artificial neural networks. The objective is to generate mathematical modelling that will be represented nanofluids' prediction of thermal conductivity and dynamic viscosity.

4. Conclusion

The capability of nanofluid in enhancing thermal and rheology properties is really encouraging for the next generation of the working fluid. Even though the pressure drops increases with higher nanofluid viscosity however the presence of more than one type of nanoparticles in preparing nanofluid can further enhance the base fluid heat transfer capability. Due to the pressure drop, more energy is required for circulating the nanofluids. This circumstance might affect the pump specifically where the pump is overworking in supplying the nanofluid consistently into the working zone. For that reason, the viscosity of hybrid nanofluid must be controlled wisely in getting a suitable range of viscosity level. Furthermore, appropriate selection of nanoparticle materials, shape and size as well as type of base fluids, with or without surfactant is crucial to get the optimum condition of nanofluid in terms of physical, thermal and rheological properties. From the literature review, it can be concluded that hybrid nanofluids exhibit better performance than single nanofluid and base fluid. Therefore, hybrid nanofluids have greater potential as the future working fluid in cooling and heating which regards the enhancement of thermal-physical properties of single nanofluids. Thus, more experimental works must be carried out to further understand the behaviour of hybrid nanofluids in terms of the effect of nanoparticle shape, size, concentration and the application of surfactant particularly on both thermal conductivity and dynamic viscosity as well as to explore its great potential. With the huge potential of hybrid nanofluids in terms of thermal-rheology properties, the elevation of overall engineering performance is realistic to be achieved.

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