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Comprehensive review of principle factors for thermal conductivity and dynamic viscosity enhancement in thermal transport applications: An analytical tool approach

K. Ramachandran[a,*], K. Kadirgama[a,b], Omar I. Awad[a,c], D. Ramasamy[a,b], M. Samykano[a,b], W.H. Azmi[a,b]

[a] *Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia*
[b] *Automotive Engineering Centre, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia*
[c] *State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China*

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ABSTRACT

In past decades, nanofluid science has been widely investigated for thermal related activities. In thermal transport applications, thermal conductivity and dynamic viscosity are closely related to cooling system performance enhancement. The genuine anomaly behind thermal conductivity and dynamic viscosity enhancement in nanofluid is still undiscoverable. In this paper, comprehensive study on principle factor behind thermophysical property enhancement focusing on thermal conductivity and dynamic viscosity is conducted. Thus, a detailed review of existing experimental results for thermal conductivity and dynamic viscosity enhancement are compiled and discussed in this manuscript. Analytical tool approach such as fishbone diagram and summary tables are used to highlight principle factor for thermal conductivity and dynamic viscosity enhancement. The principal factor which influences the thermal conductivity is shape of the particle, nanofluid preparation, interfacial layer, Brownian motion, particle clustering and aggregation. Meanwhile, the principal factor influencing dynamic viscosity is the physical behavior of the particle, nanofluid preparation, particle clustering and aggregation. The optimum nanofluid should have high thermal conductivity and minimum viscosity. High thermal conductivity is mandatory for maximum heat absorption in thermal transport applications. Meanwhile, minimum viscosity ensures less pressure drop which reduces the power consumption and increases the overall efficiency of the system.

1. Introduction

Excessive heat is always an unwanted element in thermal transport applications. Most practical method to eliminate these excessive heat is by exposing to the cooling medium, using efficient heat transfer fluid, near to hot surface area and by leaving excessive heat removed by heat convection method. Through this methods, the heat from high gradient (hot medium) is transferred to the low gradient (cold medium) until an equilibrium condition is reached. Generally, heat absorption capability is determined by thermal conductivity value which differs for each fluid. Also heat transfer fluid plays an important role in heat absorption for various industrial applications such as in automotive radiator, power plant condenser, electronics cooling and general cooling purposes. The most common and widely used heat transfer fluid is ethylene glycol, water and oil base cooling fluid [1–5]. The major problem with these fluids is; it has a low thermal conductivity value which produces poor performance in heat removal and cooling applications [6–8]. It also has limited thermophysical property. As such, a new approach is in need to be figured to maximize the heat absorption [1,2,9,10]. The development in thermal transport fluid should be primarily focusing on having high thermal conductivity properties as it is vital to fulfill the industrial requirement for massive heat transfer for cooling and heat absorption purposes [6]. As a remedy, Maxwell [11] encountered this thermal conductivity delinquent in conventional heat transfer fluid by adding microsized particles into basefluid. This method is shown to work well, however, the major drawbacks are faster sedimentation, instability and produce erosion on the rotating component since the micro-sized particle is big in size and heavy [5]. Alternatively, the microsized particle is replaced with nanosized particle by Masuda, Ebata and Teramae [12], which produces a better result and shows

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* Corresponding author.
E-mail address: omaribr78@gmail.com (K. Ramachandran).

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promising future. Since then, various type of nanoparticle has been dispersed in base fluids to study the thermal conductivity and dynamic viscosity behavior of the fluid [1,5,13]. Unfortunately, a comprehensive review focusing on the principle factor for thermal conductivity and dynamic viscosity enhancement yet to be available. Thus, the main objective of this study is to highlight the principle factor that contributes to thermal conductivity and dynamic viscosity enhancement using analytical tool for better understanding.

2. Nanofluids

Any particle with a diameter in the range of 1 nm – 100 nm is labeled as nanoparticle and the mixture after suspension of nanoparticles in any base fluid is known as nanofluid. Masuda, Ebata, Teramae and Hishinuma [14] is the pioneer contributor to this technology; they used Al_2O_3, SiO_2 and TiO_2 nanoparticle to study the thermal conductivity and dynamic viscosity behavior of the nanofluid. A preliminary research study by Vajjha and Das [15], by using Al_2O_3 and CuO nanoparticle proves that suspension of nanoparticles into base fluid able to enhance the thermal conductivity [16,17]. Later, Tadjarodi, Zabihi and Afshar [18], have used SBA-15 suspension in ethylene glycol-water mixture to produce high thermal conductivity enhancement compared to base fluid alone. Meanwhile, several other researchers have also proved that dispersion of solid nanoparticles into base fluid able to produce drastic thermal conductivity enhancement which improves heat transfer properties compared to base fluid [19,20]. Following that many researchers have shown their interest in thermal conductivity enhancement by using various type of nanoparticles as they have promising future [6,16,19,21]. Apart from that, nanofluid also has better stability thermal performance compared to microparticle and proved more suitable to be used in cooling applications [22]. The prepared nanofluid should have two important characteristics; no sedimentation occurrence and no-agglomeration [13,23–25]. Stable nanofluid causes significant effects on thermophysical property enhancement. Since nanoparticle is nanometer-sized, the gravity impact on them is very low which delays the sedimentation occurrence [26]. Also, nanofluid is suitable to be used in microchannel sized cooling system since it prevents clogging [26]. Moreover, nanofluid also helps in reducing the settlement of particles, clogging and abrasion, while reducing energy consumption compared to the microsized fluid cooling system [27]. Usually, a small percentage of nanoparticle ($< 0.3\%$) is suspended in basefluid to enhance thermal conductivity up to 50% in real heat transfer applications [28]. It is believed that the high surface to volume ratio of the nanoparticles contributes towards the thermal conductivity enhancement [6] and literally, this has led to a smaller sized thermal management system with reduced space consumption [26]. The performance of nanofluid is highly influenced by working temperature and nanomaterial concentration [2,22,29]. High temperature helps to enhance the thermophysical property; thermal conductivity and dynamic viscosity of the nanofluid [2]. Studies proved that nanofluids can provide better thermal performance when it has high thermal conductivity and low dynamic viscosity [30,31]. High thermal conductivity is mandatory for maximum heat absorption in thermal transport applications. Meanwhile, minimum viscosity ensures less pressure drop and increase in overall cooling system efficiency.

3. Thermal conductivity enhancement

There are several techniques to measure the thermal conductivity of nanofluid, but transient hot-wire method is the most preferable since it can produce accurate and precise thermal conductivity measurement compared to other methods [20,32]. Thermal conductivity enhancement can be related to the static mechanism and dynamic mechanism of the nanoparticles [33,34]. Particles that are stationary in base fluid is known as a static mechanism. Example of the static mechanism for thermal conductivity enhancement is interfacial layer and particle aggregation. Meanwhile, movement of particles in a base fluid is classified as a dynamic mechanism. The contributing factors for thermal conductivity enhancement for the dynamic mechanism are the Brownian motion and micro convection in base fluid [33]. Chol [6] realized the potential of suspended nanoparticles in basefluid for thermal conductivity enhancement. Said et al. [35] carried out an experiment to study the effect of suspended Al_2O_3 nanoparticle in ethylene glycol-distilled water mixture and reported high thermal conductivity value compared to basefluid alone. Besides that, type, size and shape of nanoparticles, surface to volume ratio, additive, acidity, the effect of surfactant, dispersion of particle and stability of base fluid plays an important role in enhancing the thermal conductivity of the base fluid [3,27,36–39]. Thermal conductivity can be increased by adding 1–5% of nanoparticles into the basefluid. There is a controversial argument among researchers on the anomalous enhancement of thermal conductivity [40]. Turgut, Tavman et al. [3] used TiO_2 with a mean diameter of 21 nm nanoparticle to study the effect of particle volume fraction on thermal conductivity enhancement. In their experiment, at 3 vol% volume fraction, thermal conductivity enhancement was about 7.4% compared to base fluid. Yoo, Hong and Yang [27] conducted an experiment to study the effect of the area to volume ratio of nanoparticle on thermal conductivity enhancement. They conducted experiment on various type of nanoparticles; TiO_2 (25 nm), Al_2O_3 (48 nm), Fe (10 nm) and WO_3 (28 nm) in basefluid of ethylene glycol and water. Maximum thermal conductivity enhancement reported by them is 14.4% for TiO_2, 4% for Al_2O_3, 16.5% for Fe and 13.8% for WO_3. They concluded that thermal conductivity is highly dependant on size and type of the nanoparticle. Meanwhile, Eastman, Choi, Li, Yu and Thompson [17] obtained 40% thermal enhancement for Cu with mean diameter < 10 nm at volume concentration of 0.3%. Conversely, Sundar, Singh and Sousa [29] studied the effect of volume concentration of Fe_3O_4 by using ethylene glycol-deionized water mixture at volume ratio of 20:80 respectively. Maximum thermal conductivity enhancement measured is 46% at highest volume concentration of 2%, in the experiment. Leong, Yang and Murshed [41] in their research used Al_2O_3 with mean diameter of 150 nm and obtained 5% of thermal conductivity enhancement at 0.5 vol%. Murshed, Leong and Yang [42] proved that the thermal conductivity of nanoparticle has significant effect on thermal enhancement of base fluid when he obtained 40% enhancement at 5 vol% for Al rather than only 18% at same volume concentration for TiO_2. Table 1 summarizes experimental results for thermal conductivity enhancement for various types of nanofluid.

3.1. Physical of nanoparticles towards thermal conductivity enhancement

There are various nanoparticle materials used with base fluid in effort to enhance thermal conductivity of nanofluid. The thermal conductivity of the nanofluid is influenced by thermal conductivity of the nanoparticle and base fluid [44]. Studies shows that thermal conductivity of metallic nanofluid (metallic nanoparticle) is higher than nonmetallic nanofluid (nonmetallic nanoparticle) [6,45]. Meanwhile, nanofluid that contains ceramic nanoparticles has low thermal conductivity compared with metallic nanofluid [27]. Hong, Hong and Yang [39] in their experiment justify it when Fe (metallic nanoparticle) able to produce high thermal conductivity value compared to WO_3 (ceramic suspended nanoparticles). Javadi, Sadeghipour et al. [37] proved that TiO_2 and Al_2O_3 nanoparticle has better heat transfer coefficient than SiO_2. Conversely, Hong, Hong and Yang [39] claimed that nanoparticles with high thermal conductivity does not always provide drastic enhancement in thermal conductivity immediately. Researchers also felt that nanoparticle shape plays an important role in determining the thermal conductivity of nanofluid. Murshed, Leong and Yang [46] provedthat nanoparticle with spherical shape has high thermal conductivity than nanoparticle with cylinder shape. The relationship between shape of nanoparticle and thermal conductivity enhancement can be explained by the variation of area to volume fraction of each