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Thermo-physical properties of hybrid nanofluids and hybrid nanolubricants: A comprehensive review on performance

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ABSTRACT

Hybrid nanofluids and hybrid nanolubricants are very new types of research which can be prepared by suspending two or more than two dissimilar nanoparticles either in a mixture or composite form in the base fluids. The term hybrid can be considered as different materials which are a combination of physical and chemical properties to form a homogeneous phase. The main objective of synthesizing hybrid nanofluids/nanolubricants is to improve the properties of single materials where it has great enhancement in thermal properties or rheological properties that are better than individually conventional nanofluids/nanolubricants. This review summarizes the previous research on the thermo-physical properties of hybrid nanofluids/nanolubricants including methods of preparation, instrumentations, development and current progress, and hybrid performance in terms of heat transfer and pressure drop. Challenges and several applications using hybrid nanofluids/nanolubricants were also discussed. Recent studies showed that the hybrid nanofluids/nanolubricants improved the performance of the single type suspended nanoparticles. Various studies of hybrid nanofluids have been carried out to investigate the heat transfer performance and thermal conductivity; however, other thermo-physical properties such as viscosity, density and specific heat have been neglected. In addition, few studies on hybrid nanolubricants were done only for thermo-physical properties. Thus, a comprehensive study on heat transfer and the other thermo-physical properties are necessary to show the potential of hybrid in engineering applications.

1. Introduction

Nanofluids are defined as the dispersion of metallic or non-metallic nanoparticles with principal dimensions of less than 100 nm in a liquid. From previous investigations, the efficiency of heat transfer greatly enhances the thermo-physical properties such as thermal conductivity, thermal diffusivity, viscosity and convective heat transfer coefficients of nanofluids that have been dispersed in a continuous medium such as water, ethylene glycol, and engine oil [1]. Keblinski et al. [2] conducted investigations on thermal conductivity of Cu nanoparticle and found that the thermal conductivity for ethylene glycol and oil increased with the dispersion of less than 1% volume concentration of Cu nanoparticles. Different studies by various researchers were conducted with nanofluids prepared in different base fluids and concentrations using metal or metal oxide nanoparticles such as Al_2O_3 (aluminium oxide), Cu (pure copper), CuO (copper oxide), Fe_3O_4 (iron oxide), SiC (silicon carbide), SiO_2 (silicon dioxide), TiO_2 (titanium oxide), ZnO (zinc oxide), and ZrO_2 (zirconium dioxide) [3–7].

In order to increase the stability of the nanofluids and to minimize the agglomeration of nanoparticles, the one-step method was chosen. The one-step method is a process of synthesizing the nanoparticles and simultaneously dispersing them in a base fluid. However, this method is not practical for industrial functions and only applicable for low vapour pressure host fluids [8]. The other method of nanofluid preparation is known as the two-step method. There are two processes in this method, which are (i) synthesis of the nanoparticles in the powder form (ii) dispersion of the nanoparticles into the base fluids to form a stable and homogeneous solution [8]. Most nanofluids and nanolubricants used oxide particles and carbon nanotubes and are produced by the two-step method [9–13]. This method is usually produced in large scales because nanopowder synthesis techniques have already been scaled up to industrial production levels. However, the challenges of using the two-step method in preparing nanofluids are the agglomerations and that the nanoparticles tend to settle down quickly [8,14].

According to Hatwar et al. [8], nanofluids have potential to be used for wide applications in industries such as microelectronics, transportations,

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and manufacturing. This is because of several factors such as (i) since the nanoparticle size is small, the pressure drop is minimal, (ii) the heat transfer rate that increases because of the higher thermal conductivity and large surface area of nanoparticles in a base fluid, and (iii) nanofluids are most suitable for rapid heating and cooling systems. Application of the nanofluids in the industries is prevented by several factors such as long term stability, increased pumping power and pressure drop, nanofluid thermal performance in turbulent and fully developed regions, lower specific heat of nanofluids and higher production cost of nanofluids [8]. For instance, the common applications of nanofluids and nanolubricants are engine cooling, engine transmission oil, lubricant in automotive air-conditioning compressor, nuclear system cooling, solar water heating, refrigeration, thermal storage, bio-medical applications, defence and space applications [1,14–22].

In a continuation of nanofluid research, a few papers have recently discussed the topic of hybrid nanofluids [23–26]. Hybrid nanofluids are considered as an extension of nanofluids in research work, which can be prepared by suspending two or more dissimilar nanoparticles either in mixture or composite form in the base fluids [23]. A hybrid material is a substance that combines the physical and chemical properties. Hybrid material consisting of carbon nanotubes (CNTs) have been used in electrochemical-sensors, bio-sensors and nanocatalysts, but the use of these hybrid nanomaterials in nanofluids has not developed as such [27]. The main objective of synthesizing hybrid nanofluids is to improve the properties of single materials where great enhancement in thermal properties or rheological properties can be achieved. Furthermore, the hybrid nanofluids are expected to achieve better thermal conductivity compared to a single type of nanofluid. Investigations on hybrid nanofluids, either experimental or numerical, are very limited. Until recently, only two review papers on hybrid nanofluids have been done by Sarkar et al. [23] and Sidik et al. [28]. However, both papers concentrated on the development and the recent progress and the review was only limited to the hybrid nanofluids.

Therefore, the objective of the present work is to provide a comprehensive review on the thermo-physical properties of hybrid nanofluids and hybrid nanolubricants. The paper also reviewed the methods of preparations, instrumentations, development and current progress of hybrid nanofluids/nanolubricants. Besides that, the performance of the hybrid nanofluids are also discussed for heat transfer, pressure drop and friction factor. Lastly, the challenges and several applications of hybrid nanofluids/nanolubricants were also discussed.

2. Development of hybrid nanofluids and hybrid nanolubricants

2.1. Methods of preparation

Table 1 summarized the methods of preparing the hybrid nanofluids/nanolubricants. The two-step method is the more dominant method compared to the one-step method. There are three types of base fluids used in preparing the hybrid solution, which are water and ethylene glycol for hybrid nanofluids whereas oil based fluids and lubricant for hybrid nanolubricants. A study by Jana et al. [29] used CNT-AuNP hybrid nanofluids. First, they used different volume fractions of CNT added into the water to produce different volume fractions of CNT suspensions whereas AuNP was added to DI water to produce AuNP suspensions. After that, AuNP suspensions were added to different volume fractions of CNT suspensions to achieve CNT-AuNP suspensions. Laurate salt and DI water were added in CuNP to form CuNP suspensions. Laurate salt acted as a catalyst to enhance the stability of CuNP suspensions. Then, CNT suspensions were added in CuNP suspensions to reduce the sedimentation of CuNP and improve the stability.

Ho et al. [30,31] prepared the PCM suspensions using interfacial polycondensation and emulsion technique. The PCM suspensions were formulated by mixing appropriate quantities of MEPCM particles with ultra-pure Milli-Q water in a flask. They then dispersed the nanoparticles in the solution using an ultrasonic vibration bath. The water based hybrid nanofluids was set up by scattering Al_2O_3 nanoparticles at different mass fractions in ultra-pure Milli-Q water by utilizing an attractive stirrer. Baby and Ramaprabhu [12] synthesized MWNT by catalytic chemical vapour deposition (CCVD) and hydrogen exfoliated graphene from graphite oxide (GO). The as-synthesized HEG was not solvent in water due to the exfoliation of oxygen containing functional groups from the specimen; making it hydrophobic. So as to make it hydrophilic, HEG and MWNT was functionalized in H_2SO_4 and HNO_3 acid medium. The nanostructure of the mixture was set up by mixing the same amounts of *f*-MWNT and *f*-HEG in a specified volume of water after functionalization. Further, the arrangement was ultrasonicated for 1 h and stirred for another 24 h. The final mixture was separated, dried

Table 1
Summary of preparation methods for hybrid nanofluids.

Authors	Base fluids	Materials	Methods
Baby and Ramaprabhu [12]	Water, EG	MWNT-HEG	Two-step method
Hemmat Esfe et al. [24]	Water, EG	Cu-TiO_2	Two-step method
Suresh et al. [25]	Water	Al_2O_3-Cu	Two-step method
Gou et al. [27]	Water	MWNT-silica	Two-step method
Jana et al. [29]	Water	CNT-CuNP/CNT-AuNP	Two-step method
Ho et al. [30]	Water	Al_2O_3-MEPCM	Two-step method
Ho et al. [31]	Water	Al_2O_3-MEPCM	Two-step method
Botha et al. [32]	Transformer oil	Silver-silica	One-step method
Suresh et al. [33]	Water	Al_2O_3-Cu	Two-step method
Baghbanzadeh et al. [34]	Water	Silica-MWCNT	Two-step method
Abbasi et al. [35]	Gum Arabic (GA) + water	MWCNT/g-Al_2O_3	Two-step method
Bhosale and Borse [36]	Water	Al_2O_3-CuO	One-step method
Madhesh et al. [37]	Water	Cu-TiO_2	Two-step method
Sundar et al. [38]	Water	MWCNT-Fe_3O_4	Two-step method
Hemmat Esfe et al. [39]	Water	Ag-MgO	Two-step method
Yarmand et al. [40]	Water	GNP-Ag	Two-step method
Afrand et al. [41]	SAE40	SiO_2-MWCNTs	Two-step method
Asadi and Asadi [42]	Engine oil	MWCNT-ZnO	Two-step method
Harandi et al. [44]	EG	F-MWCNTs-Fe_3O_4	Two-step method
Soltani and Akbari [45]	EG	MgO-MWCNT	Two-step method
Yarmand et al. [46]	EG	Biomass carbon-graphene oxide	Two-step method
Selvakumar and Suresh [50]	Water	Al_2O_3-Cu	Two-step method
Han and Rhi [53]	Water	Ag-Al_2O_3	One-step method
Takabi and Shokouhmand [54]	Water	Al_2O_3-Cu	Two-step method
Mechiri et al. [69]	Vegetable oils	Cu-Zn	Two-step method