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A review on thermophysical properties of nanofluids and heat transfer applications

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ABSTRACT

This paper summarizes the important results regarding the improvement in the thermophysical properties of nanofluids. The influence of important parameters like particle's (loading, material, size, and shape), base fluid type, temperature, additives and pH value has been considered. There are many conflicting reports on the influence of parameters on thermophysical properties and the literature in this field is widespread, so this article would be beneficial for investigators to have a precise screening of a broad range of studies in this field. Further literature review of the applications of nanofluids with a particular focus on the advantages of using nanofluids in solar collectors and as coolants in automotive heat exchangers. The authors hope that this review can help in the translation of nanofluid technology from the lab scale research to industrial applications in solar collectors and automotive sector. At last, the paper identifies the opportunities for future research.

1. Introduction

The conventional thermal fluids like water, oil and ethylene/propylene glycol plays an important role in many engineering sectors such as power generation, electronic applications, air-conditioning, chemical production, heating and cooling processes, nuclear system cooling, space and defense, transportation and microelectronics. These fluids have poor thermal properties compared to solids. In order to improve heat transfer, the use of extended-surface (fins and micro channels), the vibration of the surface, suction/injection of fluids and using electrical/magnetic fields has reached to the standstill. Hence, new technologies with the prospective to enhance the thermo-physical properties of the conventional fluids have been an area of great research [1]. The solid particles exhibit superior thermal conductivities. Several studies focused on thermal properties of suspension of these solid particles in traditional fluids. The addition of these dispersed particles of millimeter or micrometer size [2,3] to the base fluid results in modification of thermophysical properties of the base fluids that ultimately leads to heat transfer enhancement. However, these millimeter or micrometer sized particles cause problems such as poor suspension, poor stability and leads to channel clogging. Recent advances in the technology have allowed the emergence of new materials with improved performance and properties compared to the traditional materials. Nanomaterials over the last decade have attracted attention from diverse research groups ranging from material science to electronic, mechanical and healthcare sector. The amazing optical, mechanical, electrical and thermal properties of nanomaterials have made them most sought after materials of the present time. This development of nanomaterials has allowed development of a new category of fluids termed as nanofluids. Different synthesis strategies are adopted for producing the nanomaterial's (normally less than 100 nm). These nanoparticles are then suspended in the conventional fluids to see their effect on the thermophysical properties of the resulting nanofluids. The term nanofluid was first used by Choi [4] in 1995 at the Argonne National Laboratory, USA. These nanofluids (Fig. 1) show better long-term stability, little pressure drop, and can have superior thermal conductivity as compared to milli/micrometer sized particles. Researchers have used certain types of materials to synthesize nanoparticles such as oxide ceramics, metal carbides, nitrides, metals (Al, Cu, Au,), nonmetals, single or multiwall carbon nanotubes (MWCNT), and functionalized nanoparticles to form nanofluids. In common, an optimized synthesis procedure is required for making stable suspensions of nanoparticles in base fluids. Based on requirement, a wide range of combinations of nanoparticles and fluids are possible. For example, various types of nanoparticles with or without surfactant molecules can be dispersed into fluids such as water, ethylene/propylene glycol, oils and other lubricants [5]. Generally, researchers used single-step (one-step) and two-step method to produce nanofluids. One-step method involves simultaneous making and directly dispersion of particles in the base fluid. This

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Nomenclature

K	Thermal conductivity ($Wm^{-1}K^{-1}$)
C_p	Specific heat ($J\,Kg^{-1}K^{-1}$)
k_B	Boltzmann constant, $k_B = 1.381 \times 10^{-23}\,J/K$
T	Temperature (K)
N	empirical shape factor, $n = 3/\psi$
μ	Viscosity ($Pa\ s$)
ϕ	nano particle volume fraction
ρ	Density (Kg/m^3)
ψ	Particle sphericity
β	ratio of the nanolayer thickness to the original particle radius, $\beta = \frac{h}{r}$
bf	Base fluid
nf	nanofluid
p	solid particle

method avoids the use of processes such as drying, storage, transportation, and dispersion of nanoparticles. Authors [6–10] used one step method in their experimental works. Nikkam et al. [11] performed the one-step fabrication of copper nanoparticles in di-ethylene glycol as base liquid, which resulted in highly stable nanofluids. Two-step method is the other most commonly used technique for preparing nanofluids. This process involves formation of nanoparticles as dry fine particles chemical / physical process. Then, in the second processing step, using various techniques like ultrasonic agitation, high-shear mixing, these nanosized powders are dispersed in base fluid. The drawback of this method is that due to the small sizes and high surface area, these nanoparticles have the tendency to combine. In order to improve the stability of nanoparticles in fluids, the most important technique is the use of surfactants [12]. Two step method was used by several researchers to prepare CNTs [13], hybrid nanoparticles [14] and several types of nanofluids [15,16,17,18–29].

Nanofluids find applications as coolants in automobile transmission, electronic cooling, drilling fluids, solar water heating, nuclear reactor, radiator etc. Numerous review articles [30–48] provide discussion on synthesis, investigation of thermophysical properties, mechanism of heat transportation in nanofluids, challenge's and applications in heat transfer. Table 1 describes the summary of review work on nanofluids by different researchers. In spite of unexpected thermophysical properties, there are contradictions in the published data. Still nanofluids confuse the researchers, offer challenges; hence, comprehensible understanding of thermophysical properties and the effect of various parameters is required. The present study reveals the comprehensive review of the thermophysical properties i.e., thermal conductivity, viscosity, specific heat based on different base fluids (water, ethylene glycol, gear oil, paraffin, and refrigerants) and nanoparticles, heat transfer applications particularly focused to solar collectors and coolants in automotive heat exchangers. Lastly, the challenges and opening issues for future research work has been discussed.

2. Thermophysical properties of nanofluids

The incorporation of nanoparticles in the base fluid leads to change in the thermophysical properties such as thermal conductivity, viscosity and specific heat that affect the convective heat transfer. Different nanomaterial's change their parameters to different extent.

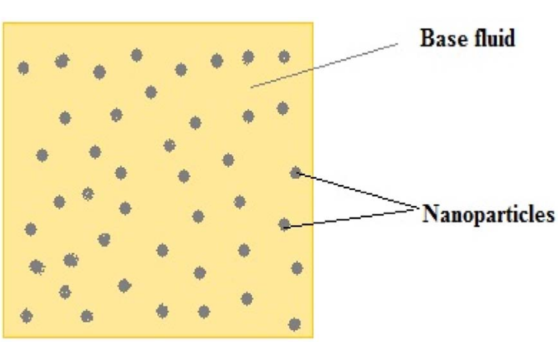

Fig. 1. Nanoparticles dispersed in base fluid.

Concentration of nanoparticles, purity level, shape and size of nanomaterial's are some of the prime factors that significantly alter the thermophysical properties. This section presents the up-to date review of the thermophysical properties of different base fluids and nanoparticles along with factors affecting the thermal conductivity.

2.1. Thermal conductivity

Many experiments as well as theoretical researches have been performed to investigate the change in thermal conductivity of nanofluids. The addition of nanoparticles in a conventional fluid increases the thermal conductivity. This is because of the Brownian motion (Fig. 2) which is a key mechanism controlling the thermal behavior of nanoparticles–fluid suspensions. The second reason is the interfacial layer (nanolayer) i.e. the liquid molecules (Fig. 3) close to a solid particle surface form layered structures. These layered structures act as a thermal bridge between nanoparticles and a bulk liquid and augments the thermal conductivity. There are little connection between this nanolayer and the thermal properties of solid/liquid suspensions. These layered molecules are present in an intermediate physical state between a bulk liquid and a solid particle. The solid-like nanolayer of liquid molecules is likely to increase thermal conductivity greater than the bulk conventional fluid [49].

Studies show that the thermal conductivity of nanofluids is higher than the base fluids [50–52]. The thermal conductivity of nanofluids can be measured by various techniques, i.e., transient hot-wire apparatus, hot disk thermal constants analyzer. The researchers have performed experiments taking different base fluids (ethylene glycol, propylene glycol, methanol, glycerol, gear oil, engine oil, paraffin etc.) and with different nanoparticles.

2.1.1. Base fluids

2.1.1.1. Water. Murshed et al. [53] used a rod-shaped and spherical shaped TiO_2 nanoparticles and prepared nanofluids by dispersing these nanoparticles in de-ionized water. The experimental result showed the improvement in thermal conductivity with an increase in particle loadings (0.5–5 vol%) and is affected by particle size and shape. The results of thermal conductivity for TiO_2 (15 nm)-water nanofluids showed a 29.70% enhancement with 5% particle volume fraction and thermal conductivity for TiO_2 (ϕ 10 nm×40 nm)-water nanofluids showed a 32.80% enhancement at same volume fraction. Rod shaped nanoparticles showed more enhancements compared to a sphere shaped. Duangthongsuk and Wong wises [54] observed the thermal conductivity of TiO_2 nanoparticles for 0.2–2 vol% dispersed in water. The thermal conductivity of nanofluids increased as the particle loading and temperature (ranging between 15 °C and 35 °C) were increased.

Buongiorno et al. [55] carried an International Nanofluid Property Benchmark Exercise (INPBE), measuring the thermal conductivity of matching samples of colloidally stable nanofluids of thirty organizations worldwide, using experimental approaches like transient hot wire method, steady-state and optical methods. They considered nanofluids having an aqueous and non-aqueous base fluid, metal and metal oxide