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State-of-art review on hybrid nanofluids

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ABSTRACT

Nanofluids have found crucial presence in heat transfer applications with their promising characteristics that can be controlled as per requirements. Nanofluids possess unique characteristics that have attracted many researchers over the past two decades to design new thermal systems for different engineering applications. Mono nanofluids, prepared with a single kind of nanoparticles, possess certain specific benefits owing to the properties of the suspended nanoparticle. However to further improve the characteristics of nanofluids, that could possess a number of favourable characteristics, researchers developed a new generation heat transfer fluid called hybrid nanofluid. Hybrid nanofluids are prepared either by dispersing dissimilar nanoparticles as individual constituents or by dispersing nanocomposite particles in the base fluid. Hybrid nanofluids may possess better thermal network and rheological properties due to synergistic effect. Researchers, to adjudge the advantages, disadvantages and their suitability for diversified applications, are extensively investigating the behavior and properties of these hybrid nanofluids. This review summarizes the contemporary investigations on synthesis, thermo-physical properties, heat transfer characteristics, hydrodynamic behavior and fluid flow characteristics reported by researchers on different hybrid nanofluids. This review also outlines the applications and challenges associated with hybrid nanofluid and makes some suggestions for future scope of research in this area.

1. Introduction

Mankind is living in the arena of advanced technologies and the past few decades are clear evidence for the exponential growth in various fields like electronics, power generation etc., where heat transfer is an integral part. This unprecedented growth demands miniaturization, improved operating and storage capacities of the devices, which in turn seeks for a new revolution in cooling technologies. In this scenario, innovative and advanced cooling methods are inevitable. Thermal management of such devices become noteworthy and thereby insists the researchers to establish an effective heat transfer medium. Various traditional heat transfer enhancement techniques like extended surfaces and mini channels took a back step by stretching them to the extent limit to improve the heat transfer rate [1,2]. A novel strategy to improve the thermal conductivity of the transferring medium is to suspend high thermal conductivity solid particles in inherently poor thermal conductive conventional fluids. Maxwell [3] is the pioneer in this area of dispersing the solid particles in a liquid medium to augment the thermal conductivity of the working fluid and gave an appropriate theoretical base to estimate effective thermal conductivity. In continuation to this, Hamilton-Crosser [4] carried out an outstanding research on particles suspended fluids and modifies the Maxwell correlation [3] to estimate various thermophysical properties more precisely. But both [3,4] dispersed micro sized solid particles in base fluids, thus their studies are limited by some flaws like the rapid settlement of the solid particles, more pumping power, wall erosion and clogging of the flow passage in the flow field. There is a big constraint to use micro fluids in micro channels. However, advancements in material technology gives a uniqueness to the heat transfer fluids by dispersing the nano dimensioned particles in host fluids. Choi [5] addressed the phenomenon of suspending nano sized particles in the base fluid and entitled this fluid as nanofluid. The most significant feature of nanofluid is, to some extent, coagulation can be suppressed. Homogeneous dispersion of particles and addition of appropriate surfactant can further suppress the agglomeration.

In recent years, several researchers reviewed and analyzed the synthesis, preparation and characterization of various nanofluids for different heat transfer applications [6–11]. Many numerical and experimental results are reported on various combinations of nanoparticles and base fluids. Among many kinds of nanoparticles, some commonly used nanoparticles are Al, Ag, Au, Cu, Fe (metals), Al_2O_3, CuO (metal oxides), SiC, TiC (carbide ceramics), AlN, SiN (nitride ceramics), SiO_2, TiO_2 (semiconductors), carbon in various forms (like nano-diamond, graphite), carbon nanotubes with single wall, double

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Nomenclature

C_p	Specific heat (J kg^{-1} K^{-1})
f	Friction factor
k	Thermal conductivity (W m^{-1} K^{-1})
m	mass (kg)
V	volume (m^3)
T	Temperature (°C)
x/D	length to diameter ratio
Nu	Nusselt Number
Re	Reynolds number
Pr	Prandtl Number

Greek letters

ρ	Density (kg m^{-3})
μ	Viscosity (N s m^{-2})
β	Thermal Expansion Coefficient (μm m^{-1} °C^{-1})
ϕ	Particle volume fraction (%)

Subscripts

bf	base fluid
hnf	hybrid nanofluid
nf	nanofluid
np	nanoparticle

wall and multi walls, fullerene and shell composites. Conventional base fluids are water, polymer solutions, transformer oil, ethylene glycol.

The fundamental issue with the mono kind nanofluids is either they have a good thermal network or better rheological properties. Mono nanoparticles solely not possess all favourable characteristics necessary for a specific application. But, many real time applications demand trade-off among several characteristics/properties of nanofluids. For example, metal oxide nanoparticle like Al_2O_3 exhibit good chemical inertness and stability, but possess lower thermal conductivity while metallic nanoparticles like Aluminum, Copper, Silver possess higher thermal conductivities, they are chemically reactive and unstable. By hybridising such metallic nanoparticles with ceramic or metal oxides, the resulting hybrid nanofluid exhibit superior thermo-physical properties and rheological behavior together with the refined heat transfer characteristics. This opens the new arena of hybrid nanofluid to use them for different heat transfer applications. Hybrid nanofluid is a homogeneous mixture of two or more nanoparticles with new physical and chemical bonds. The primary idea of hybrid nanofluid is to achieve a promising improvement in thermophysical, hydrodynamic and heat transfer properties, compared to mono nanofluids due to synergistic effect [12]. By hybridising the appropriate combination of nanoparticles, one can get the desired heat transfer effect even at low particle concentrations [13]. As hybrid nanofluids are new generation fluids, very few reviews are carried on their synthesis and preparation [14,15]. The present state of art review make an attempt to give a clear note on hybrid nanofluids and explores various synthesis methods adapted by previous researchers, distinct correlations developed to estimate their thermophysical properties, heat transfer and rheological characterization and recent research on hybrid nanofluid applications.

1.1. Review methodology

Past two decades are the clear evidence for the significant growth in research on nanofluids. In this review, papers listed in SCOPUS are only considered. Research was found to be focused on synthesis, preparation, characterization and adaptability of different nanofluids to various industrial and commercial applications. Number of papers published in the last decade pertaining to nanofluids and publication rate are summarized in Fig. 1. It is evident from Fig. 1 that there is an intense interest among the scientific community on the nanofluids research. In the year 2016 alone 1259 articles were published on nanofluids whereas 46 articles were published on hybrid nanofluids. However, from the Fig. 1, it is clear that, comparatively very less amount of research has been carried out on hybrid nanofluids.

In this review an attempt is made to consolidate the work available in literature on hybrid nanofluids, to identify challenges and provide focused perspective for future endeavors. Information from literature are grouped into sections as mentioned in the contents. The section of synthesis of nanocomposites, preparation of hybrid nanofluids, and stability of nanofluid provide the reader with reliable and tested techniques. Methods adopted to estimate the thermophysical properties of hybrid nanofluids and correlations to estimate the Nusselt number for hybrid nanofluids are also consolidated.

1.2. Applications of nanofluids

A notable improvement in heat transfer properties of nanofluid stimulates the researchers to use them in various engineering applications such as cooling of electronic apparatus, automotives, nuclear reactors, solar collectors and so on. Most of research related to nanofluids focuses on thermophysical properties and heat transfer characteristics, but, research work related to the commercial applications are relatively scarce.

In 2008, US electric power industry started using nanofluid as cooling agent and is saving 10–30 trillion Btu of energy per year, which in turn reduces 21,000 metric tons of SiO_2, 5.6 million metric tons of CO_2 and 8600 metric tons of NO_x [16]. Nuclear reactor cooling can be improved by using nanofluids as coolant [17,18]. Nguyen et al. [19] examined micro-electronic block cooling with Al_2O_3/Water nanofluid.

Increased demands on processing and storage capacities of personal computer and laptop CPUs seeks high heat transfer rate. Providing a heat pipe with different geometries and different nanofluids becomes a better choice [20–22]. Boyaghchi et al. [23] conducted experiments with CuO/water nanofluids on solar vapour absorption refrigeration system to improve heat transfer characteristics of refrigerant and reported 9.34% enhancement in its performance.

Employing the nanofluids is a viable alternative to improve the engine cooling rate and reduce the complexity of the thermal management system [24,25]. The improved heat transfer rates, give a pathway to design lighter and compact radiators, particularly for the heavy duty engines [26,27]. Adding water based aluminum and alumina nanofluids in a diesel engine fuel, improves the combustion performance [28]. During combustion, pure aluminum particles act as an oxidizing agent and alumina nanofluid serves as a catalyst. Larger contact surface area of aluminum nanoparticles accelerates the decomposition of

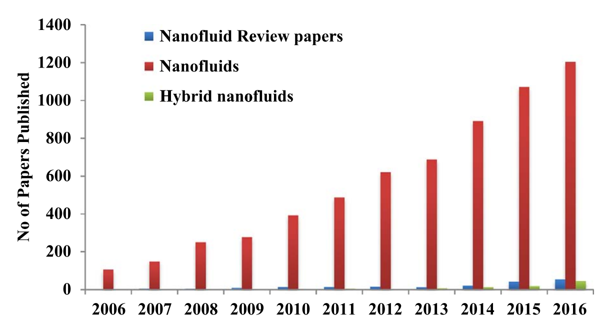

Fig. 1. Number of articles published reports by Scopus from 2006 to 2016 retrieved by the key word nanofluid and hybrid nanofluid.

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