International Communications in Heat and Mass Transfer 78 (2016) 60–67

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

A review on why researchers apply external magnetic field on nanofluids☆

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ARTICLE INFO

Available online 06 September 2016

Keywords:
Nanofluid
Magnetic nanoparticle
Magnetic field
Drug delivery
Stretched surface
Peristaltic flow
Thermal conductivity

ABSTRACT

This paper reviewed the application of external magnetic field on nanofluids. So far, nanoparticles have been used in various areas such as manufacturing, electrical and electronics, automotive and recently biomedical applications. On the other hand, nanofluids with suspension of magnetic nanoparticles have attracted noteworthy attention due to its numerous applications in industries and engineering. In line with fast development of this type of nanofluid, the purpose of this paper is to further understand the effect of external magnetic field on nanofluids properties and fluid flow, which is a key issue that influenced both the nanofluid properties and control of fluid flow for application. The conclusions and important summaries were also presented according to the data collected.

Contents

1. Introduction

Cooling is one of the most significant scientific challenges in the industrial area, which applies to many diverse productions, including microelectronics, transportation and manufacturing. Technological developments such as microelectronic devices operating at high speeds, higher-power engines, and brighter optical devices are driving increased thermal loads, requiring more advances in cooling. Low thermal conductivity of conventional heat transfers fluids such as water and oils is a primary limitation in enhancing the performance and the compactness of such systems. In addition, increasing the cooling rate by traditional technologies (i.e. fins and microchannel) has already reached their limits.

In recent years, several researchers have focused on heat transfer enhancement by modifying the thermo-physical properties of the working fluid. Nanofluid, an engineered colloidal suspension of nanoparticles in a base fluid, have been applied in many real engineering applications such as the photonics, transportation, electronics, and energy supply industries [1–5] due to its enhanced thermal conductivity and convective heat transfer coefficient compared to the base fluid [6–9]. Among the early studies, Bahiraei et al. [10] experimentally examined the effect of temperature and volume fraction on the viscosity for TiO_2–water nanofluid. They revealed that the viscosity of this nanofluid decreases

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.08.023
0735-1933/

by increasing the temperature and increases by raising the volume fraction. Experiments by Bilgins et al. [11] showed an increase for thermal conductivity by dispersion of less than 1% volume fraction of Cu nanoparticles or carbon nanotubes in ethylene glycol or oil by 40% and 150%, respectively. Good performance of nanofluid has also been confirmed by Bobbo et al. [12], who studied a double tube coaxial heat exchanger heated by solar energy using Aluminum oxide nanofluid. Later, the same authors proposed empirical correlation equations of viscosity for water based with single wall carbon nanohorn (SWCNH) and titanium dioxide (TiO_2) nanofluids.

In a difference study, Mena et al. [13] obtained a new experimental data for the viscosity of Al_2O_3 based water with ranges of low temperature and volume concentration, the results showed good agreement with benchmark data. Forced convection turbulent flow of Al2O3-water nanofluid inside an annular tube with variable wall temperature was investigated experimentally by Prajapati and Rajvanshi [14] and Ghanbarpour et al. [15]. The results showed the enhancement of heat transfer due to the presence of nanoparticle in the fluid. The turbulent flow of different nanofluids with different volume concentrations flowing through a three-dimensional channel under constant heat flux condition has been investigated by many others [16–20].

Magnetic nanoparticle suspensions and their manipulation are becoming an alternative research line and have very important applications in the field of microscale flow control in microfluidic circuits, control of fluids in microscale, and drug delivery mechanisms. In microscale, it is possible and beneficial to use magnetic fields as actuators of such nanofluids, where these fluids could move along a gradient of magnetic field so that a micropump without any moving parts could be generated with this technique. Thus, magnetically actuated nanofluids could have the potential to be used as an alternative micro pumping system [11]. The magnetic fluid expanded into thermal engineering and control of fluid since the past decade [21].

Magnetic nanofluid, also known as ferrofluid is a colloidal suspension consisting of magnetic nanoparticles with typical dimensions of about 10 nm and a carrier liquid phase [22–24]. The liquid carrier can be polar or nonpolar. Ferrofluids are different from the usual magnetorheological fluids used for dampers, brakes and clutches, formed by micron sized particles dispersed in oil. In magnetorheological, the application of a magnetic field causes an enormous increase of the viscosity, so that, for strong enough fields, they may behave like a solid. On the other hand, a ferrofluid keeps its fluidity even if subjected to strong magnetic fields. Ferrofluids are optically isotropic but, in the presence of an external magnetic field, exhibit induced birefringence. Wetting of particular substrates can also induce birefringence in thin ferrofluid layers [25].

A brief review on the literature shows that nanofluids with suspension of magnetic nanoparticles have attracted noteworthy attention due to its numerous applications in industries and engineering. In line with fast development of this type of nanofluid, the purpose of this paper is to further understand the effect of external magnetic field on nanofluids properties and fluid flow, which is a key issue that influenced both the nanofluid properties and control of fluid flow for application. In addition, we make some notes on guidelines for future research on the properties of magnetic fluids.

2. Enhancement of thermal conductivity

Crainic et al. [26] possibly the first group of researchers who attempted the use of magnetic fields to obtain new nanocomposites with the aid of the specific technology of RTM (Resin Transfer Moulding) process and the inclusion of magnetic nanofluids. The new nanocomposite, mixture between resins and the nanomagnetic fluids, contains the desired properties for the specified applications of composite materials where magnetism is important (such as radar, magnetic levitation trains, kinetic energy accumulators and electric engine rotors).

After few years, researchers initiated the study on the enhancement of thermal conductivity of nanofluids by the external magnetic field. Hong et al. [27] for the first time reported the effect of magnetic field strength and acting time on the thermal conductivity of nanofluid containing 0.01 wt.% nanotube and 0.02% wt.% Fe_2O_3 in water. Under the presence of magnetic field, the magnetic particles (Fe_2O_3) form connected networks and also tend to get somewhat oriented toward the field direction, the nanotubes are also move nearby, induce more physical contacts thus increasing the thermal conductivity. A maximum of 35% enhancement than the nanofluid without magnetic field was recorded. However, with a longer time in magnetic field, bigger clump of particles was formed and thus decreasing the thermal conductivity.

Within the same year, Wright and his team [28] measured the thermal conductivity of nanofluids containing Ni coated single wall carbon nanotube. They reported that the time to reach the maximum peak value of thermal conductivity was increased as the applied magnetic field was reduced. Thermal conductivity improvement by the aggregation of nanoparticles into clusters has been acknowledged by few researchers [29,30]. In other innovative researches, Wensel et al. [31] and Hong et al. [32] added chemical surfactant of sodium dodecylbenzene sulfonate (NaDDBS) to the solution containing single wall carbon nanotubes (SWCNTs). NaDDBS then absorbed to the surface of the nanotubes and made these surface negatively charged. While maintaining the solution at pH value of 7, positively charged metal oxides were added and aggregated with negatively charged nanotubes. Wensel et al. [31] reported that the nanofluids containing 0.017 wt.% SWCNT, 0.017 wt.% MgO and 0.17 wt.% NaDDBS at pH 7 gave 0.69 W/mK of thermal conductivity which is 10% higher than the base fluid (water). Nevertheless, the recent study by Reza et al. [33], who carried out measurements on 1 vol.% TiO_2–water nanofluid, found somewhat contradicted findings. Maximum enhancement of thermal conductivity can reach only 2.5% which is insignificant. Enhancement beyond 10% cannot be achieved because the aggregates settlement.

Wensel et al. [31] also demonstrated that under the influence of magnetic field, the maximum thermal conductivity was recorded around 0.92 W/mK, about 35% higher than the nanofluid without magnetic field. Interestingly, at higher pH, the thermal conductivity dropped back to 0.63 W/mK. One possible reason was that when pH increases, MgO becomes negatively charged and the aggregation broke. However, Reza et al. [33] found enhancement up to 167% in the thermal conductivity under the application of external magnetic field parallel to the temperature gradient direction.

The effect of the orientation of external magnetic field on the flow and thermodynamics properties of nanofluids has been investigated by few researchers. Shima and Philip [34] synthesized oleic-acid-capped magnetite nanoparticles and carried out comprehensive measurement of thermal conductivity in two different hydrocarbon based nanofluid under varying magnetite field strength and orientations. They revealed that at low particle loading, the enhancement of thermal conductivity was unnoticed irrespective of magnetic field strength. However, for nanofluid with higher particle loading, a maximum enhancement of 125% was observed at field strength of 378 G and parallel field orientation to the temperature gradient. In a recent numerical study by Song et al. [35] who analysed the magnetic field direction on nanofluid in channel, the nanofluid flow was considered laminar, incompressible and two-dimensional flow in a parallel-plate channel. A uniform magnetic field was applied in x–y plane and the angle between the direction of magnetic field and x-axis was taken from 45° to 90°. The governing equations were solved using fourth-order Runge–Kutta scheme. Their findings showed that at greater angle, the flow velocity tends to decrease due to higher Lorentz force resistance which cause high pressure drop of the flow. On the other hand, higher angle also contributes to a larger thermal conductivity normal to the walls of channel and a more uniform temperature field.