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A Comparative Study of Theoretical and Experimental Data of Thermal Conductivity Enhancement for Iron and Iron Oxide Nanofluids

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Abstract—*Nanofluid, a suspension of a base fluid and nanoparticles along with certain surfactants, has enormous ability to enhance the efficiency of thermal conduction by fluids. It has been observed that with the incorporation of solid nano particles in a fluid there is anomalous increase in thermal conductivity of the fluid and hence it has developed a great interest among researchers to utilize nanofluids for heat transfer applications. Presently, we do not find any conventional models that can satisfactorily predict the unusual behavior in thermal conductivity of these nanofluids. Various experimental investigations have revealed dependence of thermal conductivity on parameters like nanoparticle volume fraction, Temperature, nanoparticle size, surface chemistry of nanoparticles, thermal conductivity of base fluid and solid nanoparticles, interfacial layer thickness , particle movement etc. In this paper we present a comparison between experimental data and theoretical predictions based on thermal conductivity of iron and iron oxide based nanofluids, also called as Ferro-fluids or Magnetic nanofluids. It was observed that both experimental and theoretical data hinted at enhancement of thermal conductivity of nanofluid with increase in volume fraction of nanoparticles.*

1. INTRODUCTION

Nanofluids are colloidal suspensions of solid nanoparticles in a base liquid that have substantially higher thermal conductivity than the base fluids. In comparison with the traditional solid-liquid suspensions nanofluids have higher stability and due to nano-size they have higher specific surface area (that is, surface area per unit volume of particle). By adding surfactants the nanofluids can be made more stable as such clogging or agglomeration of nanoparticles is prevented. The nanofluid properties can be controlled by varying particle size , concentration, shape, surface treatment etc. The term 'nanofluid' was first coined by Choi (1995) at Argonne National Laboratories, Illinois. But Musuda et al. (1993) were the first to report improvement in thermal conductivity by addition of nanoparticles to a base fluid- observing an increase of 30% at 4.3% particle volume fraction. Although many investigations have been done since then but a definitive theory is still awaited because of lack of understanding of the basic mechanism of thermal conduction at nano-level. (Das et al.2007; Wang and Fan 2010). Due to high thermal conductivity than conventional fluids, nanofluids have high potential for application in many frontiers of engineering and technology. Saidur et al have presented a range of applications of nanofluids like Cooling of electronics, camera lenses, cell phone displays, chillers in air conditioning systems, domestic refrigerator, coolant in thermal systems of vehicles, coolant in machining, Solar energy conversion systems, in transformer oil etc.

2. MAGNETIC NANOFLUIDS

MNF are colloidal solutions of ferromagnetic nanoparticles suspended in a base liquid like water, ethylene glycol etc. Apart from having higher thermal conductivity at low particle volume fractions these smart fluids properties can tuned and and controlled using a controllable magnetic field. Phillip et al. conducted work with iron oxide dispersed in kerosene and observed an increase of thermal conductivity by 300% at a volume concentration as low as 6.3%. With a high thermal conductivity and controllability using magnetic field MNF have applications in wide areas like heat exchangers, cooling systems, intertia-damping apparatus, engine coolants, energy conversion systems. Many aqueous magnetic nanofluid in bioengineering and biomedical applications like magnetic cell separation, magnetic resonance imaging etc.

3. MODELS IN THERMAL CONDUCTIVITY OF NANOFLUIDS

One of the earliest well known work on the thermal conductivity of a solid – liquid suspensions is that of Maxwell[1]. According to this model the ratio of effective thermal conductivity of nanofluid to that of base fluid is given by:

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f + 2\varphi(k_p - k_f)}{k_p + 2k_f - \varphi(k_p - k_f)}$$

where k_{eff}, k_p, and k_f are the thermal conductivity of the nanofluid, nanoparticles and base fluid respectively. φ is the volume fraction of particles in the mixture. Although this model takes volume concentration into consideration but the particle size and shape is neglected and the interaction between particles is also neglected. In order to take shape of particles into consideration Hamilton and Crosser []extended the Maxwell model .The Hamilton Crosser model is based on the following definition of thermal conductivity for a two component mixture.

$$k_{eff} = \frac{k_P\varphi_p\left(\frac{dT}{dx}\right)_P + k_f\varphi_f\left(\frac{dT}{dx}\right)_f}{\varphi_p\left(\frac{dT}{dx}\right)_p + \varphi_f\left(\frac{dT}{dx}\right)_f}$$

where φ_p and φ_f are volume percentages of nanoparticles and base fluid respectively in the nanofluid. As per Hamilton and Crosser (1962) model the ratio of effective thermal conductivity of nanofluid to that of base fluid is given by:

$$\frac{k_p + (n-1)k_f - (n-1)\varphi\left(k_f - k_p\right)}{k_p + (n-1)k_f + \varphi\left(k_f - k_p\right)}$$

where k_p is the thermal conductivity of the solid phase, k_f is the thermal conductivity of the base fluid, φ is the volume fraction of particles, and n is the empirical shape factor given by

$$n = \frac{3}{\Psi}$$

where Ψ is the sphericity, whose value for spherical and cylindrical shapes is 1 and 0.5 respectively. Furthermore, sphericity is defined as the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particle. Maxwell Garnet model is a modification for Maxwell model. According to Maxwell Garnett model effective thermal conductivity is given by :

$$\frac{k_{eff}}{k_f} = \frac{(1-\varphi)(k_p + 2k_f) + 3\varphi k_p}{(1-\varphi)(k_p + 2k_f) + 3\varphi k_f}$$

Bruggeman's model can be applied to spherical particles with no limitations on the particle volumetric concentrations, as per Bruggeman's model

$$(\varphi)\frac{k_p - k_{eff}}{k_p + 2k_{eff}} + (1-\varphi)\frac{k_{bf} - k_{eff}}{k_{bf} + 2k_{eff}} = 0$$

Hence, by solving the equation for a particular combination of nanoparticle and base fluid thermal conductivities and the volume percentage of solid phase in the nanofluid, we can obtain the effective thermal conductivity of the nanofluid. Another model for thermal conductivity enhancement ratio was proposed by Wasp. This model is gives quite similar results to the Hamilton Crosser model. As per Wasp model:

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f - 2\varphi\left(k_f - k_p\right)}{k_p + 2k_f + \varphi\left(k_f - k_p\right)}$$

Sundar et al. based on their experimental investigation on Fe_3O_4/water nanofluid, proposed a correlation which relates effective thermal conductivity of nanofluid with the volume concentration of nanoparticles and further the effect of temperature is also taken care of by substituting the base fluid thermal conductivity at that particular temperature. The proposed correlation is as follows:

$$\frac{k_{eff}}{k_{bf}} = (1 + 1.05\phi)^{0.1051}$$

Wang et al[8] proposed a fractal model to calculate thermal conductivity of nanofluids. Their model is based on improvement of effective medium theory and could successfully predict the thermal conductivity for CuO-deionized water nanofluid.

$$\frac{k_{eff}}{k_f} = \frac{(3\phi - 1)\left(\frac{k_p}{k_f}\right) + (3(1-\phi) - 1) + \sqrt{\Delta}}{4}$$

where Δ is given by

$$\Delta = 3(\phi - 1)\left(\frac{k_p}{k_f}\right) + [3(1-\phi) - 1]^2 + 8\left(\frac{k_p}{k_f}\right)$$

Minsta [7] conducted experiments on copper oxide and alumina based nanofluids and presented the following equation to predict the thermal conductivity of nanofluid

$$\frac{k_{eff}}{k_f} = 1 + 1.72\phi$$

Timofeeva et al. [6] suggested suggested a similar model after experimentation with TiO2 nanofluids based on effective medium theory

$$\frac{k_{eff}}{k_f} = 1 + 3\,\varphi$$

4. EXPERIMENTAL INVESTIGATIONS

Although a lot of work has been done on thermal conductivity of nanofluids, very little is found in literature with respect to thermal conductivity improvement in magnetic nanofluids. Some of the selected research work is discussed in this section.

Phillip et al [1.]. studied the enhancement of thermal conductivity in magnetite based nanofluids which were prepared by dispersion of magnetite nanoparticles in carrier (base) fluid . In their study they observed an increase in the thermal conductivity ratio with the increase in the magnetite particle volume fraction and a maximum thermal conductivity ratio enhancement of 23% at 7.8% particle vol % in absence of magnetic field. Abarishi et al. [2.] conducted work on thermal conductivity of MNF prepared by the dispersion of Fe_3O_4 nanoparticles in distilled water. They used tetramethyl ammonium hydroxide to improve the dispersion of iron oxide nanoparticles in the base fluid. Their results showed that the realative thermal conductivity increases with the increase in volume fraction of iron oxide particles. The highest relative thermal conductivity ratio enhancement was found to be 11.5% at a particle volume fraction of 3%. Another investigation on iron based nanofluids was carried out by Hong et al[3.].They investigated the thermal conductivity enhancement of an ethyleneglycol- Fe based magnetic nanofluid and observed a non-linear increase in the thermal conductivity with increase in volume fraction. Qiang et al.[4]conducted experimental investigation on the effect of magnetic nanoparticle volume fraction on the thermal conductivity of nanofluids by dispersing iron nanoparticles in water. They investigated the variation in thermal conductivity of MNF with a regular increase in the particle concentration. Their study revealed increase in thermal conductivity of the nanofluid with increase in particle concentration and an enhancement of 14.9% at 5.0% volume % of iron particles. Sunadar et al. [5] experimentally investigated the effective thermal conductivities of water-based nanofluids containing Fe3O4 nanoparticles and their result confirmed dependence of effective thermal conductivity on the particle volume concentration and temperature. The observation included a higher thermal conductivity ratio of 1.48 at 2.0% volume concentration at 60 C temperature with respect to water (base carrier fluid).

5. COMPARISON BETWEEN EXPERIMENTAL DATA AND THEORETICAL MODEL PREDICTIONS

The comparison between experimental values and calculated values of effective thermal conductivity based on various thermal conductivity models is shown in Fig 1-6. It is observed that in all the cases the ratio of thermal conductivity increases with the volume concentration. In Fig. 1 comparison of experimental data from Sundar et al [5] with values from theoretical models demonstrates that the models cannot predict thermal conductivity with much accuracy, although Bruggeman model is relatively accurate with respect to the experimental values. In Fig 2 experimental values of Qiang Li et al [4] are compared with theoretical values and the models generate satisfactory values close to experimental ones except for bruggeman model which exhibits large positive deviation. In fig 3 at higher values of volume concentration the theoretical values from Timoneffa, Minsta and M-G model show accurate results with respect to the experimental data. In fig 4 Timoneffa model predicts the results with accuracy followed by Minsta model but at the same time both Hamilton- Crosser and Bruggeman model predict the values with least accuracy._In Fig. 5 Timoneffa and bruggeman model exhibit resemblance with the experimental values but not satisfactorily. Whereas Bruggeman model predicts nearly exact value at 0.015 volume concentration, it overestimates the thermal conductivity ratio at higher volume concentration.

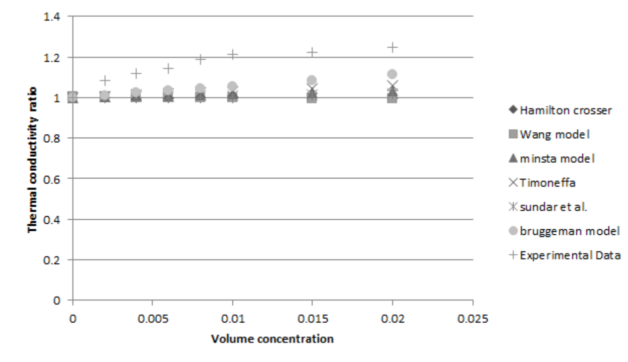

Fig. 1 comparison of theoretical models with experimental data of Sundar et al

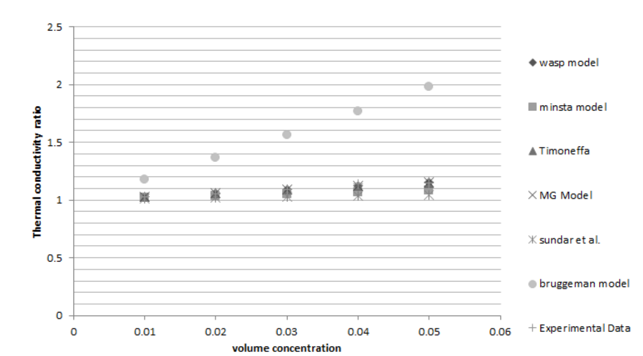

Fig. 2 comparison of theoretical models with experimental data of Qiang li et al

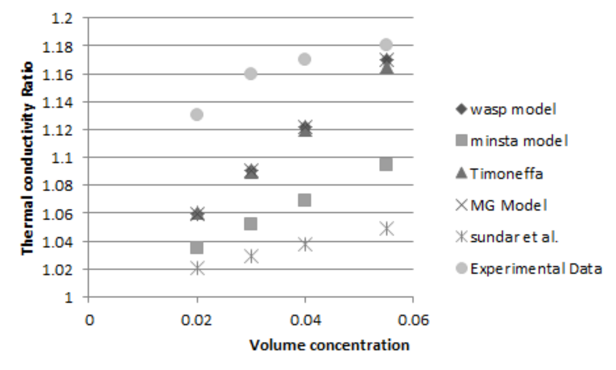

Fig. 3 comparison of theoretical models with experimental data of Hong et al

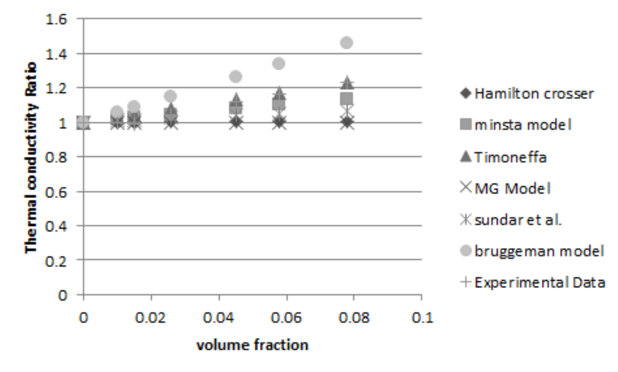

Fig. 4 comparison of theoretical models with experimental data of Phillip et al

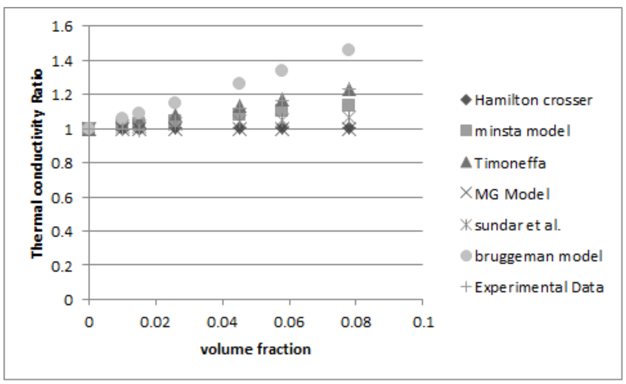

Fig. 5 Comparison of theoretical models with experimental data of Abarishi et al

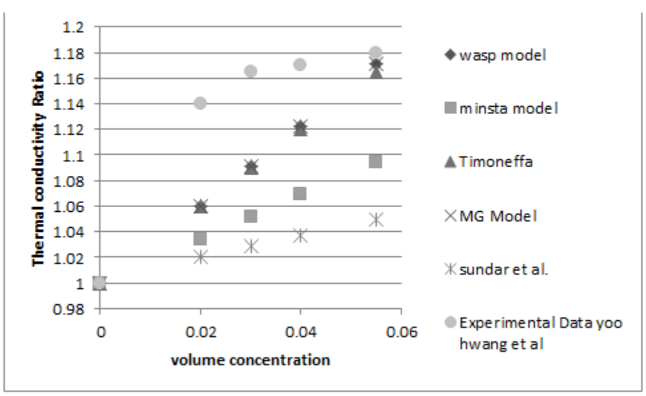

Fig. 6 Comparison of theoretical models with experimental data of Hwang et al

6. CONCLUSION

It was observed that although some models can predict enhancement in thermal conductivity but most of these models are not able to generate satisfactory results for all volume concentrations. Hence, further investigations are required to develop a model that can predict the thermal conductivity enhancement of nanofluids accurately.

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