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Review of magnetorheological fluids and nanofluids thermal behaviour

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Abstract. Magnetorheological fluids are smart materials with the capability to reversibly change from liquid to near solid state under the presence of external magnetic fields. The interest in magnetorheological fluid as a heat transfer medium is due to the possibility of controlling its flow and heat transfer process through external magnetic field. This review highlights on the recent developments of magnetorheological fluid and nanofluid in the field of thermal behaviour. Special emphasis is paid to the understanding of their thermal conductivity property by several parameters which include particle volume fraction, shape and size of particles, materials of particles and base fluid, and magnetic field. Reports indicate that the increase with particle volume fraction and magnetic field strength may increase the thermal conductivity of magnetorheological fluid. From the theory and experimental given, relationship between these parameters and thermal conductivity can be found.

1. Introduction

Magnetorheological fluids are intelligent materials made of magnetic particles that have the ability to rapidly change their flow characteristics in the presence of an applied magnetic field. Some of the unique characteristics of magnetorheological fluids are adjustable viscosity, rapid response time and high dynamic flow strength [1]. However, the field-dependent thermal conductivity of magnetorheological fluids has received much less attention despite its importance in heat dissipation of active damping devices and potential new applications but this is not the case for nanofluids. Nanofluids on the other hand are two-phase media that consist of liquid and solid nanometer-scale particles. The interest to nanofluids relates to the fact that even low concentration of nanoparticles can significantly change its thermal behaviour. Practical application of nanofluids is connected with a possibility to create a high performance liquid heat carrier. By considering the fact that metallic solids possess better thermal properties than fluids, nanofluids contained with suspended solid particles are expected to exhibit significantly higher thermal properties than that of conventional heat transfer fluids [2].

This review mainly focuses on the most relevant progress during the recent years and further application in future regarding thermal behaviour of magnetorheological fluids. In particular, it deals with the most significant experimental results in magnetorheological fluids and nanofluids relating to thermal conductivity for heat transfer applications. The analysis is made to identify the influence of different factors on the expected results. It is expected that this review provides a framework for the future direction of studies on magnetorheological fluids to enhance its thermal properties.

2. Particle Volume Fraction

Solid suspension is a type of fluid consists of small solid particles for various purposes which some of the notably discovered suspension types are magnetorheological fluid, ferrofluid, electrorheological fluid, and nanofluid. Generally, these suspensions comprise 3 main elements; solid particles, base fluid and additives. Numerous studies have been conducted on solid particles with mostly by varying the particle volume fraction to enhance the suspension performance.

In magnetorheological fluid, it is found that thermal conductivity increases in the absence of magnetic field as particle volume fraction is increased. From figure 1, the thermal conductivity ratios were recorded at approximately 1.4 and 2.0 for 10 vol% and 20 vol% of iron based magnetorheological fluid, respectively. The measured thermal conductivities are normalized by the oil/grease base fluid conductivity of 0.1242 W/m K [3].

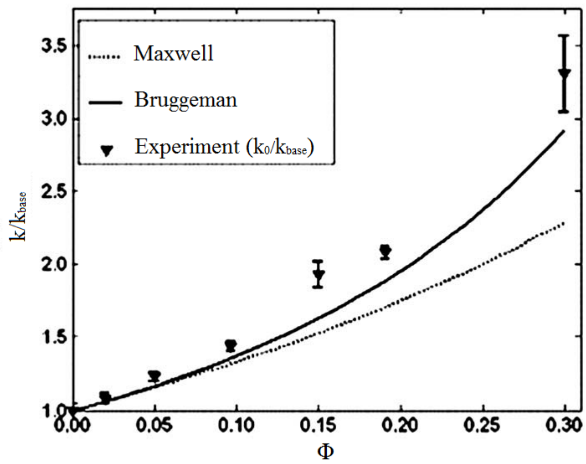

Figure 1. Measured zero-field thermal conductivity for varying particle volume fraction [3].

Additionally, in the presence of magnetic field, the thermal conductivity of magnetorheological fluid will increase when particle volume fraction and magnetic field strength are increased. At 2 mT of magnetic field strength, the thermal conductivity values for 20 vol% and 40 vol% of iron based magnetorheological fluids were recorded at approximately 0.42 W/m K and 0.46 W/m K, respectively. While at 15 mT of magnetic field strength, the thermal conductivity values increased again to approximately 0.49 W/m K and 0.54 W/m K, respectively [1]. However, the ratio of thermal conductivity in bulk magnetorheological fluids without magnetic field and with 290 kA/m of magnetic field is approximately 1.3. The experiment conducted to produce this finding was using bulk iron based magnetorheological fluids with particle volume fraction up to 33 % along the magnetic field direction. The result indicates that increasing particle volume fraction is insignificant on enhancing huge amount of thermal conductivity [4]. In other study, a relationship between thermal conductivity and particle volume fraction was reported to be in linear correlation. The linear correlation model as shown in equation (1) and (2), were applied in an experiment and the result shows that the model is able to evaluate the sedimentation stability of the magnetorheological fluids [5].

$$k_{eff} = 0.0245\Phi - 0.08 \tag{1}$$

$$k_{eff}/k_f = 0.167\Phi - 0.53 \tag{2}$$

where $10 \leq \Phi \leq 50$

k_{eff} is the magnetorheological fluid effective thermal conductivity,
k_f is the thermal conductivity of the base fluid,
Φ is the particle volume fraction

By comparison with magnetorheological fluid, it is also found that the nanofluid thermal conductivity increases with the increase of particle volume fraction in nanoparticles [6]. As shown in figure 2, the increase of up to 1.5 vol% of Al_2O_3 nanoparticles resulted in thermal conductivity increase at about 5 % [7].

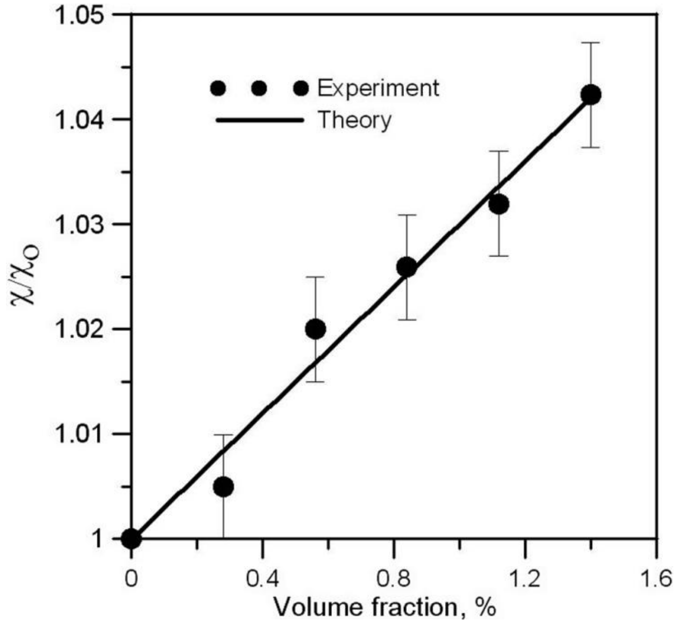

Figure 2. Relative thermal conductivity versus nanoparticles volume fraction [7].

3. Shape and Size of Particles

The magnetorheological particles are traditionally in spherical shape while typical particle sizes are in the range of micrometres [8]. The size distribution range of magnetorheological particles is 0.5-20 μm. Surface morphology of carbonyl iron particles is observed with a scanning electron microscope (SEM) and the images with size distributions are shown in figure 3 [9]. Although shape and size of particles were proven to affect thermal conductivity in nanofluids, no reports found any description in magnetorheological fluid [10]. Nevertheless, mechanism of shape and size of particles in affecting the thermal conductivity remains relevant in the case of magnetorheological fluid.

The enhancement of effective thermal conductivity due to particle shape effect is strongly reduced by interfacial effects proportional to the total surface area of particles. For example in nanofluid research, the thermal conductivities of Al_2O_3 nanofluids with different particle shapes measured at room temperature are presented in figure 4 as a function of nanoparticle volume fraction [10]. This result indicates spherical shape of particles produce least enhancement in thermal conductivity as in the magnetorheological fluid. Therefore, introduction of cylinder shaped particles or additive will improve the thermal conductivity properties of magnetorheological fluid.

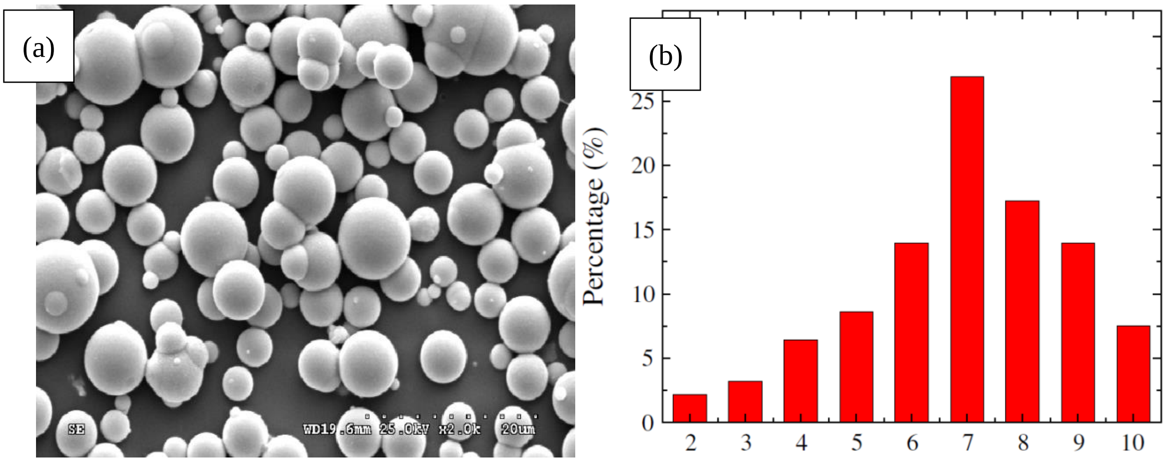

Figure 3. (a) SEM images and (b) size distributions of carbonyl iron particles [9].

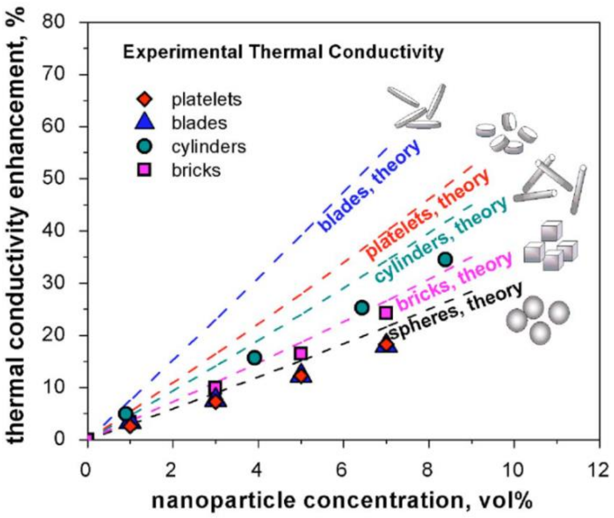

Figure 4. Experimentally measured thermal conductivity of Al_2O_3 nanofluids in ethylene glycol/H_2O for corresponding particle shapes [10].

Furthermore, it was found that the reduction of particle size with temperature rise enhanced the thermal conductivity ratio of a solid suspension. Taking nanofluid as an example, the thermal conductivity ratios could be enhanced by up to 14.7 % for 20 nm nanoparticles at 50 °C as can be seen in figure 5. The experiment used water based Al_2O_3 nanofluids with different nominal diameters of 20, 50, and 100 nm under varied temperatures [11].

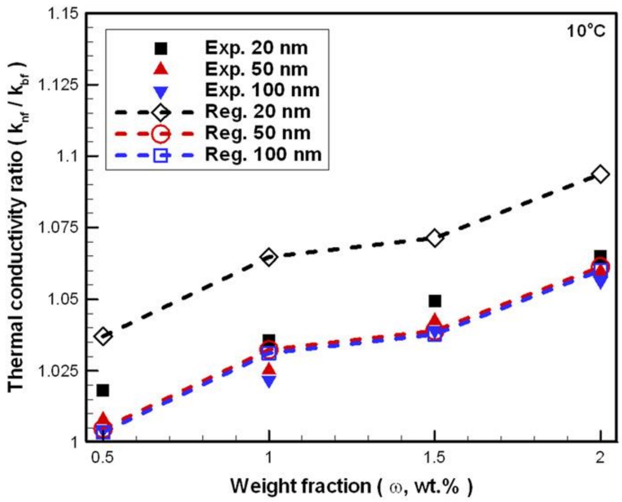

Figure 5. Dependence relationship between weight fraction and thermal conductivity ratio of Al_2O_3/water nanofluid with different particle sizes at 50 °C [11].

This is further evidenced by an experiment conducted on three different Al_2O_3 nanofluids with 11, 47 and 150 nm sized nanoparticles where the effective thermal conductivity is normalized by the base fluid thermal conductivity. The thermal conductivity enhancement at 70 °C is merely 5 % for 150 nm sized nanoparticles, but increased further to 10 % and 20 % for 47 nm and 11 nm sized, respectively [12]. Hence, it is proven that thermal conductivity will be improved by reducing particle size and can be applied to magnetorheological fluid.

4. Material of Particles

In practice, the most frequently used material of particles in magnetorheological fluid is carbonyl iron powder. It has several important features such as high magnetic permeability, low remnant magnetization, fine particle size and common availability. The iron content is 97–99 % and the surface morphology is typically spherical [9]. However, the lack of research on material of particles in enhancing the thermal conductivity of magnetorheological fluid has forced this review to look into nanofluids. At room temperature (300 K), the thermal conductivity of carbonyl iron powder is 80.4 W/m K [13]. Alternatively, the thermal conductivities of common materials of particles used in solid suspensions are summarized in table 1.

Table 1. Thermal conductivities of several solid suspension particles at 300 K [14].

Suspension particles	Thermal conductivity, k (W/m K)
CIP	80.4
TiO_2	8.04
CuO	17.65
Al_2O_3	39
Al	237
Cu	401

It is found that the thermal conductivity enhancement is higher for water based Cu nanofluids compared to water based Al_2O_3 nanofluids. The thermal conductivity ratios for Cu nanofluids and Al_2O_3 nanofluids are 1.12 and 1.10, respectively. This result is attributed to the higher thermal conductivity of Cu nanoparticles than Al_2O_3 nanoparticles [15]. Likewise, water based Al_2O_3 nanofluid showed a higher enhancement of thermal conductivity compared with TiO_2 nanofluids with respect to particle volume fraction. While there was only 9 % enhancement of thermal conductivity with TiO_2 nanoparticles, 11 % thermal conductivity enhancement was observed with Al_2O_3 nanoparticles, which is attributed to the higher thermal conductivity of Al_2O_3 against TiO_2 [16].

On the other hand, it is found that metallic particles are giving higher enhancements of thermal conductivity than oxide particles. For instance, by using ethylene glycol as the base fluid, 11 % and 17 % of thermal conductivity enhancement were recorded for the nanofluids with 150 nm and 45 nm sized Al_2O_3 nanoparticles, respectively. Whereas 27 % of enhancement was observed for nanofluid with 80 nm Al nanoparticles, metallic nanofluids thus proved to have higher enhancement of thermal conductivity than oxide nanofluids [17]. Despite of possessing lower thermal conductivity than metallic particles like Al in this case, it is expected that carbonyl iron particles to contribute a substantial enhancement of thermal conductivity in magnetorheological fluid. Either way, the metallic nanoparticles can also be as an additive so as to enhance the thermal properties of magnetorheological fluid.

5. Material of Base Fluid

The main element of a magnetorheological fluid is the base fluid which serves as a continuous insulating medium. It also has a strong impact on the fluid performances. Currently, a commonly used base fluid is the silicone oil due to its wide operating temperature range, strong anti-oxidation ability and some other important characteristics. As material of base fluid has yet to become a focal study in enhancing thermal conductivity of magnetorheological fluid, it is more sensible to look into research areas in nanofluids. Silicone oil has a thermal conductivity of 0.14 W/m K [18]. Meanwhile, the thermal conductivities of other common base fluids used in solid suspensions can be seen in table 2.

Table 2. Thermal conductivities of several base fluids at 300 K [14].

Base fluids	Thermal conductivity, k (W/m K)
Silicone oil	0.14
Deionized water	0.607
Ethylene glycol	0.255
Engine oil	0.145

When considering a theoretical model to predict the thermal conductivity of a solid–liquid mixture, the Maxwell model as shown in equation (3) can be used which is applicable to statistically homogeneous and low volume fraction of solid suspensions with randomly dispersed, uniformly sized and non-interacting spherical particles [19]. The equation (3) also shows that the thermal conductivity of base fluid has a very close relationship with the thermal conductivity of particles. This relationship as shown in equation (4) can be used to obtain the thermal conductivity enhancement or thermal conductivity ratio (without %) of a solid suspension [20].

$$\frac{k}{k_f} = \frac{k_p + 2k_f + 2\Phi(k_p - k_f)}{k_p + 2k_f - \Phi(k_p - k_f)} \quad (3)$$

where

k is the thermal conductivity,
k_f is the thermal conductivity of the base fluid,
k_p is the particle thermal conductivity,
Φ is the particle volume fraction

$$\text{Thermal conductivity enhancement, } \% = \frac{(k_p - k_f)}{k_f} \text{ x } 100 \quad (4)$$

Most of the studies have shown an increased thermal conductivity enhancement with decrease in thermal conductivity of the base fluid. For example in nanofluids, as can be observed in figure 6, dramatic improvement in thermal conductivity of graphene oxide nanosheets suspension is seen for a base fluid with lower thermal conductivity. This experiment on thermal conductivity of nanofluids comprises several base fluid materials like liquid paraffin (0.24 W/m K), propyl glycol (0.206 W/m K), ethylene glycol (0.255 W/m K) and distilled water (0.58 W/m K) [21]. Hence in theoretically, magnetorheological fluid would have a good thermal conductivity ratio as silicone oil has a very low thermal conductivity combined with the high thermal conductivity of carbonyl iron particles.

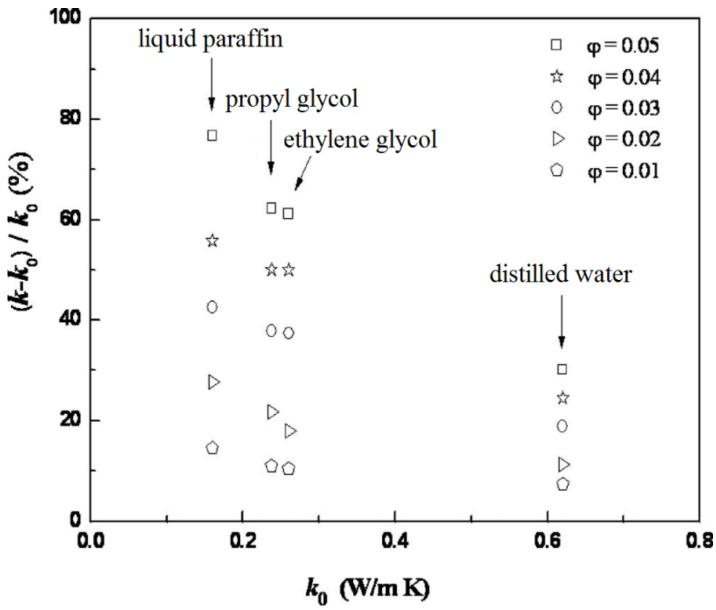

Figure 6. Thermal conductivity enhancement ratios as a function of the thermal conductivities of the base fluids with different volume fraction [21].

6. Strength and Direction of Magnetic Field

It is found that thermal conductivity of magnetorheological fluid increases with increasing magnetic field in the temperature intervals from 0 to 50 °C and from 50 to 100 °C. The substantial enhancement of the thermal conductivity is by almost 188 % at magnetic field of 15 mT as can be seen in table 3 [1].

Table 3. Thermal conductivity enhancement of magnetorheological fluids with respect to an applied magnetic field H = 15 mT [1].

	0-50 °C at 150 G		50-100 °C at 150 G	-20-0 °C at 150 G	
	ΔT = 35 K (%)	ΔT = 20 K (%)	ΔT = 15 K (%)	ΔT = 20 K (%)	ΔT = 15 K (%)
40SM	12	18	134	-42	-2
40SQ	9	11	50	-29	-8
20SM	14	3.9	188	-25	-6
20SQ	20	21	36	-7	0.2
5SM	29	32	78	-25	-4
5SQ	23	34	95	-31	-0.2

Direction of the magnetic field also has a strong influence on the thermal conductivity, with the maximum being achieved when the field was parallel to the direction of thermal gradient. As in figure 7, for parallel alignment of the magnetic field, thermal conductivity increases with increasing magnetic field strength while for perpendicular alignment, the thermal conductivity has an inverse relationship to the magnetic field strength [22].

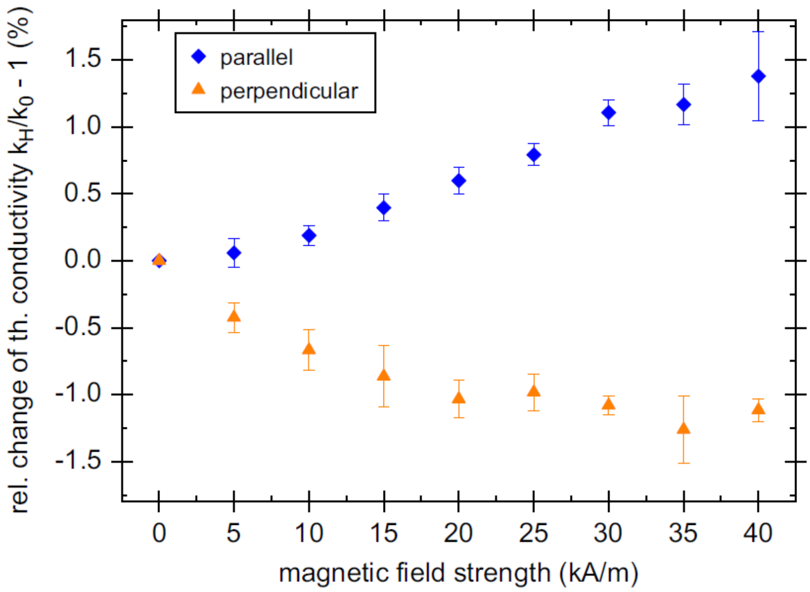

Figure 7. Relative change of thermal conductivity depending on magnetic field strength and orientation against heat flux direction [22].

In particular, the increase in thermal conductivity under external magnetic field is attributed to the effective conduction of heat through the chainlike structures formed under magnetic field when the dipolar interaction energy becomes greater than the thermal energy [23]. Additionally, hysteresis was found in which when the thermal conductivity is enhanced by the magnetic field, it remained high until the fluid is disturbed to break the particle chains. By referring to figure 8, once the suspension is magnetized to 202 kA/m, the thermal conductivity remains constant with decreasing field and only returns to its initial zero field value if the suspension is stirred [3].

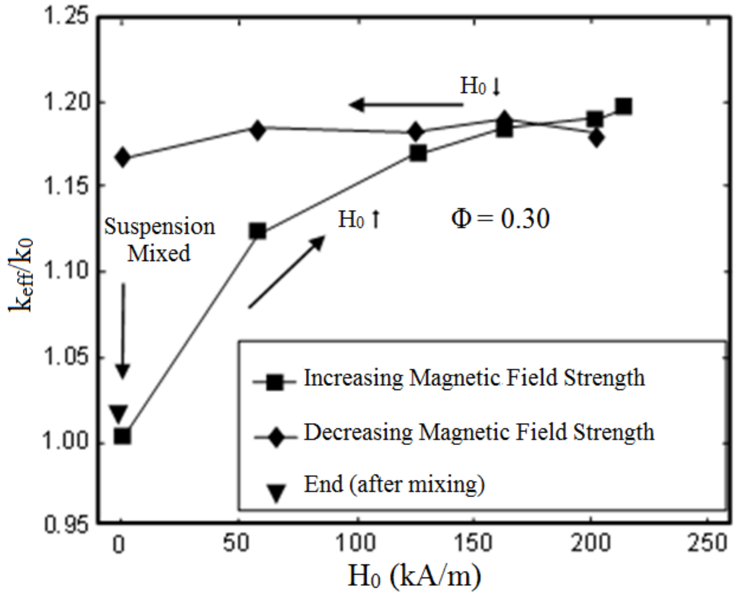

Figure 8. Thermal conductivity ratio of magnetorheological fluid with 0.30 vol% of iron depends on time history of the applied magnetic field [3].

7. Conclusions

A review of the studies conducted on magnetorheological fluids and nanofluids thermal behaviour with special attention on their thermal conductivity property was conducted. The increase in thermal conductivity has been studied according to variations in the following parameters which are particle volume fraction, shape and size of particles, material of particles, material of base fluid, and strength and direction of magnetic field. Although there are several studies on the enhancement of thermal conductivity of magnetorheological fluids from 0.42 W/m K to 0.54 W/m K, they are still room for improvement to enable optimization of the fluids to be used in practical applications. The development of this area is still challenged by many aspects ranging from the preparation and characterization to design and applications. The potential applications of magnetorheological fluids with better thermal properties would be like thermomagnetic convection and heat pipe. Further research must be related to understanding the thermal conductivity mechanisms enhancement. More detailed studies are necessary on improving magnetorheological fluids for heat transfer applications especially in the off and on-state conditions.

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