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A review on thermo-physical properties and heat transfer applications of single and hybrid metal oxide nanofluids

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ABSTRACT

Numerous investigators have explored nanofluids extensively for different types of nanomaterials either the single nanoparticles or hybrid types. This is due to their advantages in thermal properties together with its contribution to the enhancement of heat transfer performance. This paper highlights a complete assessment on thermo-physical properties of single and hybrid metal oxide nanofluids and their heat transfer applications. The paper presents an overview of the thermo-physical properties characterizations namely thermal conductivity, dynamic viscosity, density and specific heat. Furthermore, summaries on the performance of forced convection heat transport and recent developments of the oxide nanofluids are presented. The numerical and experimental studies related to forced convection heat transfer using oxide nanofluids were presented. The thermal conductivity of oxide nanofluids was improved to a maximum of 40% enhancement in the literature. Meanwhile, the heat transfer augmentation up to 60% was reported by various studies. Most of the literatures confirmed the capability of nanofluids to improve the heat transfer efficiency and simultaneously insignificant increments in pressure drop. Hence, the oxide nanofluids are recommended for applications in various engineering systems.

Keywords: nanofluids; thermal conductivity; dynamic viscosity; thermo-physical properties; heat transport.

INTRODUCTION

Nanofluids can be defined as nano-sized particles with less than 100 nm which is suspended in conventional base fluids such as water, ethylene glycol, and oil. In the early 1990s, the nanofluids were pioneered by Masuda et al. [1] and Choi [2] with a new idea of using nanoparticles in thermal systems to develop an efficient heat transfer fluid. Subsequently, numerous studies were conducted and widely merged in engineering applications such as automotive, manufacturing process, medical, renewable energy and many more. Most of the fundamental studies were investigated the thermo-physical properties of nanofluids mostly on thermal conductivity and dynamic viscosity [3-5].

Common oxide nanomaterials such as Zinc oxide (ZnO), Silicon dioxide (SiO_2), Copper oxide (CuO), Aluminum oxide (Al_2O_3), Titanium oxide (TiO_2), Iron oxide (Fe_3O_4), Magnesium oxide (MgO) and Zirconium oxide (ZrO_2) were being used in preparation of oxide nanofluids. Oxide nanoparticles have been used widely in the thermo-properties investigation and heat transfer performance evaluation of nanofluids. The oxide nanoparticles were considered in most nanofluids studies because of the production cost that is considerably lower than other types of nanomaterials. They are also commercialized and are widely used in various sectors such as automotive, coatings, filtration, army, energy, oil and gas, cosmetics, and electronics. Iron oxide or known as Fe_3O_4 has superparamagnetic properties where their magnetization properties can randomly flip directions under the influence of temperature. Meanwhile, magnetization surplus will be cancelled by thermal agitation for a condition in which the external magnetic field is removed. Thus, loss of magnetization can prevent aggregation, and hence help the stability of suspended nanoparticles in nanofluids. In addition, some advantages of Aluminum oxide or Al_2O_3 are chemically stable, mechanical strength enhancement and applicable for electrical insulating. Al_2O_3 in composite provides high barrier, fire-resistant, thermal fatigue resistance, stiffness, fracture toughness, creep resistance, resilience, and wear resistance. Meanwhile, the advantages of Silicon dioxide or SiO_2 are outstanding thermal stability, attractive mechanical properties, high strength and stiffness. The nanofluids were recommended for many applications. A review for adoption of nanofluids in PEM fuel cell was done by Zakaria et al. [6]. In addition, studies related to application of nanofluids in engineering applications were undertaken by various researchers [7, 8].

Nanofluids have been widely explored by various investigators for different types of nanomaterials either the single nanoparticles or hybrid types. This is due to their advantages in thermal properties along with contribution to the improvement in the heat transfer performance. Currently, numerous numbers of studies were performed by various investigators mostly on oxide nanofluids. However, the review on oxide nanofluids for single nanoparticles or hybrid types and their heat transfer applications is limited in literature. Present paper is therefore aimed at reviewing the latest studies of thermo-physical properties by emphasizing on the oxide nanofluids and their heat transfer applications.

NANOFLUID PREPARATION AND STABILITY

According to Lee et al. [9], low cost, long-term stability and great fluidity are the most crucial preconditions of the nanofluids for practical applications in the heat transport system. The step of nanofluid preparation is essential before proceeding to the thermo-physical properties and heat transfer characteristics of the nanofluids. Several reviews on nanofluid preparation and stability were presented by various investigators [4-7] by providing the development on recent studies. Based on reviews by Babita et al. [10] and Suganthi and Rajan [11], the preparation of nanofluids can be summarized with the following methods:

i. *One-step method*: A technique which incorporate the production of nanoparticles with the synthesis of nanofluids. Example: Inert gas condensation, chemical reduction, pulsed wire evaporation and arc-submerged nanoparticle synthesis system (ASNSS).

ii. *Two-step method*: Two stages of preparation are considered in this method. First, nanomaterials are produced in the form of dry powder. Then, the powdered nanomaterials are directly dispersed into the base fluid. Adoption of tools that rely either on the utilization of mechanical energy or surface chemistry or both are the key to the successful preparation of nanofluids by the two-step method. According to Manna [12], this method is suitable for preparation of oxide nanofluids.

Some special techniques are required to enhance and prolong the stability of nanofluids [10, 11] and are given by the following treatments:

i. *Chemical treatment*: Utilization of chemical reactant and process like adding surfactants, pH alteration and surface modification of the nanoparticles.

ii. *Physical treatment*: Employment of physical process such as magnetic stirring, ultrasonication, homogenization and mechanical milling.

The stability observation can be divided into two methods namely, the qualitative and quantitative measurement. The stability analysis of nanofluids can be conducted through qualitative methods such as sedimentation techniques and visual observation. Camera photography or submerged tray technique are usually used in the evaluation of the sedimentation. It was stated that the simplest method to observe the stability condition of nanofluids is visually. The visual approach was practiced by many investigators [13-16]. One can photograph the sample as often as possible until separation layer appears in the fluid. The sedimentation of nanoparticles was observed with time and the thickness of separation layer was recorded for further assessment of stability condition. There is no standard time for the sample to show separation layer since it can be influenced by several factors including size and shape of particles, preparation method used, and concentration of the sample [13, 15]. In another paper, Nabil et al. [17] were considered qualitative method to evaluate the stability of their samples by using sedimentation techniques and visual observation. The samples were observed for a month and found in good stability with no evident of sedimentation.

On the other hand, the quantitative method is the most reliable technique to measure the level of nanofluid stability. It can be done through measurement of zeta potential, diffractometer and electron microscopy [18, 19]. These methods require scientific instruments and more complex equipment are expected. However, the indicative information is more reliable and accurate to establish the stability of nanofluids. Abdolbaqi et al. [20] were used FESEM with × 3,000,000 magnification to evaluate the characterization of Al_2O_3 nanoparticles suspended at different ratio of water and Biogylcol (W/BG) mixture. The median particles size from the FESEM analysis was quantified at 13 nm and mostly spherical in shape. Similarly, Chiam et al. [21] also studied the characterization of Al_2O_3 nanoparticles but dispersed in different ratio of water and ethylene glycol (W/EG) mixture. They obtained similar average size of 13 nm for Al_2O_3 nanoparticles and appeared in spherical shape. In addition, some researchers tend to use relative and comparative techniques to measure the state of nanofluid stability by using Ultraviolet-Visible (UV-Vis) spectroscopy [22] and density measurements [23].

THERMO-PHYSICAL PROPERTIES OF OXIDE NANOFLUIDS

The measurement and estimation of thermo-physical properties of nanofluids mainly comprises the four main properties namely, thermal conductivity, viscosity, density and specific heat. These properties are essential for the determination of the overall heat transfer performance of nanofluids. The thermo-physical properties are measured using scientific instruments or estimated from the available models in literature. Several factors that affect the thermo-physical properties are such as types of materials, nanoparticle concentration, size and shape, base fluid, and operating temperature [13, 24-28]. These factors are discussed in this section by focusing on the trend and significant findings for oxide nanofluids from numerous literatures. Various studies were conducted to investigate the properties performance for single oxide nanofluids such as Al_2O_3, SiO_2, TiO_2, CuO, ZnO, Fe_3O_4 and MgO nanofluids. Meanwhile, some studies for hybrid or composite nanofluids are used in combination of the oxide nanoparticles or any other types of nanomaterials [15, 29-31]. The following section discussed in details the related studies for thermo-physical properties of oxide nanofluids.

Thermal conductivity

Hemmat Esfe et al. [32] conducted a study on thermal conductivity of Al_2O_3 nanoparticles in ethylene glycol (EG) for volume concentration of 0.2 to 5.0%. The transient hot wire method by the KD2 Pro instrument was employed in the measurement of the thermal conductivity. The results indicated that the effective thermal conductivity of Al_2O_3/EG nanofluids increased with increasing nanoparticle concentration and temperature. They showed maximum enhancement up to 12.7%. At higher concentrations of more than 1.0%, the effect of temperature on the effective thermal conductivity was found to be more tangible. Enhancement of thermal conductivity was found due to the Brownian motion with a high rate of collision between particles. Zakaria et al. [6] used Al_2O_3 nanoparticles dispersed in several ratios for water/EG mixture from 0 to 100% by volume. The thermal conductivity of Al_2O_3 nanofluids was measured for volume concentrations of 0.1 to 0.5% and temperature of 20 °C. A decrease in thermal conductivity was discovered when the content of EG in the mixture increased but increased with the increase of volume concentration of nanofluids. The maximum enhancement was observed for 0.5% concentration and EG content of 100%.

Sonawane et al. [33] studied on thermal conductivity of TiO_2 nanofluids in three base fluids of water, EG and paraffin oil. The improvement in thermal conductivity for the TiO_2/water nanofluids was found to be greater than TiO_2/EG and TiO_2/paraffin oil with a maximum enhancement of 22.13%. The low-viscosity fluids (water has lower viscosity than EG and paraffin oil) permit particles to interact more rapidly with one another. Therefore, the Brownian motion of nanoparticles in water based fluids is higher than others. SiO_2 is a common type of oxide nanomaterial. Guo et al. [34] investigated the thermal conductivity of SiO_2 nanofluids in mixture of water and EG. The EG content by volume was varied from 0 to 100%. The thermal conductivity of the nanofluids was conducted for 0.3% weight concentration and temperature of 25 to 45 °C. The findings showed that the thermal conductivity decreased with increasing EG content at a constant temperature. In addition, the thermal conductivity of SiO_2 nanofluids increased with increasing temperature for similar EG content.

CuO is also a common oxide nanoparticle and used in preparing single and hybrid nanofluids. Agarwal et al. [35] performed a study on thermal conductivity of CuO in base fluid of water, EG and engine oil. The investigation was performed at temperature of 10 to 70 °C and volume concentration of 0.25 to 2.0%. According to their results, the thermal conductivity enhancement was observed up to 40, 27 and 19%, respectively for CuO in water, EG and engine oil. Nemade and Waghuley [36] investigated a novel approach for thermal conductivity enhancement with CuO/water nanofluids. The evaluation was conducted at 0.5% concentration for temperature of 30 to 80 °C and probe sonication time of 15 to 60 minutes. They found that 18% enhancement of thermal conductivity was achieved for 60 minutes sonication time in comparison to the base fluid. Furthermore, the thermal conductivity of nanofluids for all sonication time was enhanced with increasing temperature. This was the result of the incessant collision between particles and base fluid, as well as influenced by large Brownian viscosity. The study also concluded that the CuO nanofluid exhibits good thermal and heat transfer characteristics and hence it was recommended for renewable energy applications.

Hybrid and composite nanofluids of oxide nanoparticles were investigated by various researchers. Ho et al. [37] obtained 13% enhancement of thermal conductivity for Al_2O_3+MEPCM in water nanofluids. The nanofluids was prepared for 2 to 10% weight concentration. The thermal conductivity was measured by using KD2 Pro thermal property analyzer at various temperatures of 25 to 40 °C. In another paper, Suresh et al. [38] prepared hybrid nanofluids with a combination of Al_2O_3 with Cu nanoparticles. They were considered 90:10 ratio of Al_2O_3 to Cu dispersed in water. The thermal conductivity was measured at a constant temperature of 32 °C. The highest enhancement was observed up to 12.11% for 2% volume concentrations. Further, Charab et al. [39] used combination of Al_2O_3 and TiO_2 nanoparticles in water to prepare composite nanofluids. The average size of particle, pH and concentration were given by 20 nm, 3.8 and 1.0%, respectively. They measured the thermal conductivity using the transient hot wire method at constant temperature of 25 °C. The results revealed that the stability of the sample became the major contribution to the non-linearity in thermal conductivity of composite nanofluids. In another paper, Nine et al. [40] combined the Al_2O_3 and MWCNT nanoparticles to prepare hybrid nanofluids for concentrations of 1.0 to 6.0 wt.%. They found that the thermal conductivity enhancement of hybrid nanofluids with spherical shape particles was lesser than cylindrical shape particles.

Toghraie et al. [41] measured the thermal conductivity of TiO_2+Zn in EG nanofluids for volume concentrations of 0.1 to 3.5% and temperatures of 25 to 50 °C. They observed that the thermal conductivity of nanofluids increased significantly with increasing temperature and volume concentration of nanofluids. The maximum enhancement of 32% was obtained with 3.5% volume concentration and 50 °C of temperature. In another paper, Hemmat Esfe et al. [32] used CuO and TiO_2 nanoparticles in water/EG mixture. The thermal conductivity of the hybrid nanofluids was measured for temperature range of 30 to 60 °C. Maximum enhancement was obtained for 2.0% volume concentration and 60 °C of temperature. Later, Megatif et al. [42] combined TiO_2 and CNT nanoparticles to prepare hybrid nanofluids with weight concentrations of 0.1 to 0.2%. The thermal conductivity was measured at 25 to 40 °C by using the transient hot wire method of the KD2 Pro analyzer. They found that the augmentation in thermal conductivity was observed up to 20.5% for 0.2% weight concentration and temperature of 25 °C. Batmunkh et al. [43] procured silver (Ag) and TiO_2 nanoparticles in the preparation of hybrid nanofluids. In their study, they used a combination of small Ag nanoparticle size (15 nm) with larger particle size of TiO_2 (300 nm). The thermal conductivity of the hybrid nanofluids was measured at temperatures of 15 to 40 °C. They concluded that the thermal conductivity of TiO_2 nanofluids improved by introducing the flattened Ag nanoparticles.

Madhesh et al. [44] prepared hybrid nanofluids of TiO_2+Cu with the average size of 55 nm. The measurement of the thermal conductivity was taken by using the laser flash method for volume concentrations of 0.1 to 2.0% and temperature ranging from 30 to 90 °C. They found that the thermal conductivity was 1.065 times higher than water base fluids. In another study by Baghbanzadeh et al. [45], hybrid nanoparticles with a combination of SiO_2 and MWCNT were prepared for two different ratios of 80:20 and 50:50. The thermal conductivity of the hybrid nanofluids was measured for 0.1 to 1.0% weight concentration at temperature of 27 and 40 °C. Their findings revealed that the enhancement in thermal conductivity was found to a maximum of 23.3% for temperature of 40 °C and 1.0% volume concentration. On the other hand, Nabil et al. [30] investigated the thermo-physical properties of SiO_2+TiO_2 nanoparticles in water/EG mixture. They measured the thermal conductivity of hybrid nanofluids for 0.5 to 3.0% volume concentration and temperature of 30 to 80 °C. The maximum enhancement of 22.8% was obtained at 3.0% volume concentration and temperature of 80 °C.

Baby and Sundara [46] studied the synthesis and transport properties of CuO nanoparticles with decorated graphene (HEG) in water-EG mixture. The thermal conductivity of the hybrid nanofluids was measured at a constant temperature of 25 °C. The results displayed that the improvement of thermal conductivity was approximately 28% for 0.05% volume concentration. Meanwhile, Nine et al. [47] prepared hybrid nanofluids with both nanoparticles from copper element and dispersed in water. They used Cu+Cu_2O with 30 nm average diameter. They only studied for 2.0% weight concentration and the thermal conductivity was measured at temperature of 15 to 40 °C. Their study revealed that the thermal conductivity of the hybrid nanofluids improved further with 1.014 times higher than base fluid. Table 1 shows the summary of previous work regarding the thermal conductivity enhancement of oxide nanofluids for single type and hybrid type nanofluids.

Table 1. Summary of thermal conductivity enhancement for oxide nanofluids.

Nanofluids (Range of concentration)	**Measurement method / Instrument (Temperature)**	**Significance enhancement (%) / Findings**	**References**
Al_2O_3 in EG (0.2-5.0 vol.%)	THW / KD2 Pro (24-50 °C)	Maximum enhancement (12.7%)	Hemmat Esfe et al. [32]
Al_2O_3 in W/EG (0.1-0.5 vol.%)	THW / KD2 Pro (20 °C)	Maximum enhancement at ϕ = 0.5% for EG content at 100%	Zakaria et al. [6]
TiO_2 in water, EG, paraffin oil (1.0-6.0 vol.%)	THW / KD2 Pro (room temperature)	Maximum enhancement (22.13%) for TiO_2/water	Sonawane et al. [33]
SiO_2 in EG/W (0.3 wt.%)	THW / TC 3020L (25-45 °C)	At fixed EG content, the thermal conductivity of nanofluids increased with increasing of temperature	Guo et al. [34]
CuO in water, EG, engine oil (0.25-2.0 vol.%)	THW / KD2 Pro (10-70 °C)	Enhancement: 40%, 27% and 19%, for CuO in water, EG and engine oil, respectively	Agarwal et al. [35]
CuO in water (0.5 vol.%)	THW / KD2 Pro (30-80 °C)	Enhancement (18%) at 60 minutes sonication time	Nemade and Waghuley [36]
Al_2O_3+MEPCM in water (2-10 wt.%)	THW / KD2 Pro (25-40 °C)	Maximum enhancements (13%) at PCM suspension ω_{pcm} 10 wt.%, nanoparticles ω_{np} 10% weight concentration	Ho et al. [37]
Al_2O_3+Cu in water (0.1-2.0 vol.%)	THW / KD2 Pro (32 °C)	Maximum enhancement (12.11%) at ϕ = 2%	Suresh et al. [38]
Al_2O_3+TiO_2 in water (1.0 vol.%)	THW / - (25 °C)	Nonlinear behavior was observed for thermal conductivity of nanofluids versus FVC of TiO_2	Charab et al. [39]

Al_2O_3+MWCNT (1.0-6.0 wt.%)	-	Hybrid nanofluids with spherical particles performed lower increment in thermal conductivity than cylindrical shape particles	Nine et al. [40]
ZnO+TiO_2 in EG (0.1-3.5 vol.%)	THW / KD2 Pro (25-50 °C)	Maximum enhancement (32 %) at ϕ = 3.5% and 50 °C	Toghraie et al. [41]
TiO_2+CuO in water/EG (1.0-2.0 vol.%)	THW / KD2 Pro (30-60 °C)	Correlation models show excellent agreement with experimental results	Hemmat Esfe et al. [32]
TiO_2+CNT in water (0.1-0.2 wt.%)	THW / KD2 Pro (25-40 °C)	Maximum enhancement (20.5%) at ϕ = 0.2% and 25 °C	Megatif et al. [42]
TiO_2+Ag in water (1.0-3.0 wt.%)	THW / LAMBDA System (15-40 °C)	Flattened “Ag” particles can be used to enhance thermal conductivity	Batmunkh et al. [43]
TiO_2+Cu in water (0.1-2.0 vol.%)	Laser flash / NETZSCH LFA 447 NanoFlash (30-90 °C)	Maximum enhancement of 1.065 higher than base fluid	Madhesh et al. [44]
SiO_2+MWCNT in water (0.1-1.0 wt.%)	THW / KD2 Pro (27 / 40 °C)	Maximum enhancement (23.3%) at ϕ = 1.0% and 40 °C	Baghbanzadeh et al. [45]
SiO_2+TiO_2 in water/EG (0.5-3.0 vol.%)	THW / KD2 Pro (30-80 °C)	Maximum enhancement (22.8%) at ϕ = 3.0% and 80 °C	Nabil et al. [30]
CuO+HEG in water/EG	- (25 °C)	Maximum enhancement (28%) at ϕ = 0.05% and 25 °C	Baby and Sundara [46]
Cu+Cu_2O in water (0.3 wt.%)	- (15-40 °C)	Maximum enhancement of 1.014 times	Nine et al. [47]

Dynamic viscosity

Hamid et al. [48] carried out an experiment on dynamic viscosity of Al_2O_3 nanofluids for 0.5 to 2.0% volume concentration. They studied the viscosity measurement for three different ratios of water-EG base fluid (60:40, 50:50, 40:60) and at various temperatures of 30 to 70

°C. The findings revealed that the viscosity of Al_2O_3/EG nanofluids exhibit an increasing trend when particle loading increased but decreased exponentially with increasing temperature. In another paper, Anoop et al. [49] investigated the rheological behavior of Al_2O_3 nanoparticles in silicone oil. The measurement was undertaken at room temperature with various pressures for up to 100 MPa and different shear rates of 5 to 1021 s^{-1}. The weight concentrations of the nanofluids were prepared for 2.0 to 8.0%. They found that the nanofluids behaved as a non-Newtonian fluid within the range of the concentration in their study. In addition, the nanofluids was observed to have shear-thinning behavior at higher shear rates and within all pressures. The critical shear rate (when shear thinning occurs) was found to be significantly affected by the particle loading.

Dynamic viscosity measurements of TiO_2 nanoparticles in Bioglycol-water (BG/W) mixture was undertaken by Abdolbaqi et al. [50]. The nanofluids was prepared for volume concentrations of 0.5 to 2.0%. The base fluid ratios of BG/W were given by 20:80 and 30:70. The measurement was conducted for temperatures of 30 to 80 °C. The viscosity of TiO_2 in BG/W nanofluids increased with increasing concentration but decreased with increasing temperature. The maximum viscosity rise was obtained at 1.53 times higher than the base fluid at 2.0% concentration, temperature of 70 °C and base ratio of 30:70. Later, Khedkar et al. [51] performed measurements at room temperature for viscosity evaluation of TiO_2 nanoparticles in EG based nanofluids. The TiO_2/EG nanofluids was prepared for up to 7.0% volume concentration. The results indicated that the viscosity linearly rose with increasing of volume concentration. The nanofluids was confirmed to have Newtonian behavior with the shear thinning nature.

In another paper, Abdolbaqi et al. [50] measured the dynamic viscosity for SiO_2 nanoparticles in BG/W mixture for two ratios of 20:80 and 30:70. They prepared the nanofluids for volume concentrations of 0.5 to 2.0% and measured the viscosity at temperature of 30 to 80 °C. The maximum enhancement of SiO_2 nanofluids with 1.38 times higher than the base fluid was obtained for 2.0% volume concentration, 30:70 (BG/W) base ratio and temperature of 70 °C. Żyła and Fal [52] conducted a study on viscosity of SiO_2/EG at a constant temperature of 25 °C. The sample of nanofluids were prepared for 1.0 to 5.0% mass concentrations. They discovered that the nanofluids exhibited as Newtonian fluids in the range of study and increased linearly with concentration. The maximum increment of viscosity was observed at 5% mass concentration for up to 1.3905 times greater than the base fluid.

Ghasemi and Karimipour [53] investigated the viscosity for CuO nanoparticles in liquid paraffin. They prepared the nanofluids for 0.25 to 6.0% weight concentration. The viscosity was measured at temperatures of 25 to 100 °C with variations of shear rate from 13 to 159 s^{-1}. They found that the enhancement of nanoparticle load lead to viscosity increments from 55 to 60% in the range of study. Inversely, the rise in temperature resulted in viscosity decrement. The viscosity of CuO/paraffin nanofluids increased for 1.5% concentration. Meanwhile, the change in viscosity was observed not highly tangible for concentrations below 1.5%. Akhavan Behabadi et al. [54] used ZnO nanoparticles in EG to investigate the viscosity behavior. The weight concentration and temperatures were varied from 1.75 to 10.5% and 15 to 55 °C, respectively. Similar trends were observed by them with the viscosity increasing with increase of concentration, but decreasing with increase of temperature. In addition, the rheological evaluation of ZnO/EG nanofluids behaved as Newtonian in the range of study.

For the case of hybrid nanofluids, Asadi and Asadi [55] conducted an experimental study on viscosity of MWCNT+ZnO in engine oil for concentrations of 0.125 to 1.0%. The viscosity measurement was conducted at temperatures of 5 to 55 °C. The outcomes revealed that the viscosity increased up to 45% with increasing concentration. Meanwhile, the dynamic viscosity of the nanofluids decreased by 85% with increasing temperature. The nanofluids also showed a Newtonian behavior within the scope of concentration and temperature study. In another study, Soltani and Akbari [56] measured the viscosity for MgO+MWCNT hybrid nanoparticles dispersed in EG for volume concentrations up to 1.0%. The measurement of viscosity was conducted at temperatures of 30 to 60 °C. They found that the hybrid MgO+MWCNT nanofluids behaved as Newtonian fluid in the range of study. A similar trend was observed by them for viscosity increments up to 168% with increasing concentration.

Akilu et al. [57] investigated the viscosity of three hybrid nanoparticles of TiO_2+CuO+C in EG based fluids. The viscosity was measured at temperatures of 30 to 60 °C and volume concentrations of 0.5 to 2.0%. The hybrid nanofluids were confirmed to behave as Newtonian fluid by investigating the rheological behavior. Furthermore, the viscosity of the hybrid nanofluids was observed to increase as the concentration increased and enhanced to 80% maximum at 2.0% volume concentration. In another study for hybrid nanofluids, Nabil et al. [30] measured the viscosity for TiO_2+SiO_2 nanoparticles in water/EG mixture. The viscosity measurement was performed at temperatures of 30 to 80 °C and volume concentrations of 0.5 to 3.0%. The results indicated that the viscosity was influenced by concentration and temperature. The highest average relative viscosity of TiO_2+SiO_2 nanofluids was obtained for up to 62.5% increment for 3.0% volume concentration. The Newtonian behavior also was observed by them for TiO_2+SiO_2 nanofluids in the range of study.

Shahsavar and Bahiraei [58] evaluated the dynamic viscosity for Fe_3O_4+CNT hybrid nanofluids. They used different concentrations for both nanoparticle components in the hybrid nanofluids. For instance, the concentration for Fe_3O_4 nanoparticles varied from 0.1 to 0.9% and 0 to 1.35% for CNT nanoparticles. They found that the viscosity for Fe_3O_4+CNT hybrid nanofluids decreased with the increment of shear rate, hence exhibited as non-Newtonian behavior. The viscosity increased with increasing of CNT or Fe_3O_4 concentration and decreased with increasing of hybrid nanofluid temperature. Table 2 shows the summary of previous work regarding the dynamic viscosity measurements of oxide nanofluids for single type and hybrid type nanofluids.

Table 2. Summary of dynamic viscosity measurements for oxide nanofluids.

Nanofluids (Range of concentration)	**Measurement method / Instrument (Temperature)**	**Significance findings**	**References**
Al_2O_3 in W/EG (0.5-2.0 vol.%)	Rotational spindle / Brookfield Rheometer (30-70 °C)	Viscosity increased with the increased of particle loading but decreased exponentially with the increased of temperature	Hamid et al. [48]
Al_2O_3 in silicone oil (2.0-8.0 wt.%)	Rotor-bob geometry / Chandler Viscometer (Room temperature)	At higher shear rate within all the pressures, the nanofluids have shear-thinning behavior. Classification: Newtonian	Anoop et al. [49]
TiO_2 in BG/W (0.5-2.0 vol.%)	Rotational spindle / Brookfield Rheometer (30-80 °C)	Viscosity increased with the increasing of concentration but decreased with the increasing of temperature. Maximum enhancement with 1.53 times at ϕ = 2.0% and 70 °C for ratio 30:70	Abdolbaqi et al. [50]
TiO_2 in EG (0-7.0 vol.%)	Rotational / AR-G2 Rheometer (Room temperature)	Viscosity linearly increased with volume concentration. Classification: Newtonian.	Khedkar et al. [51]
SiO_2 in BG/W (0.5-2.0 vol.%)	Rotational spindle / Brookfield Rheometer (30-80 °C)	Viscosity increased with the increasing of concentration but decreased with the increasing of temperature. Maximum enhancement with 1.38 times at ϕ = 2.0% and 70 °C for ratio 30:70	Abdolbaqi et al. [50]
SiO_2 in EG (1.0-5.0 wt.%)	Rotational / HAAKE MARS 2 Rheometer (25 °C)	Viscosity linearly increased with the increased of nanoparticles concentration. Maximum enhancement with 1.3905 times at ϕ = 5%. Classification: Newtonian	Żyła and Fal [52]
CuO in liquid paraffin (0.25-6.0 wt.%)	Rotational spindle / Brookfield Rheometer (25 °C)	Maximum enhancement (55-60%). Rise in temperature resulted in viscosity decrement. At ϕ < 1.5%, the change in viscosity is not highly tangible	Ghasemi and Karimipour [53]
ZnO in EG (1.75-10.5 wt.%)	Rotation / Kinexus Rheometer (15-55 °C)	Viscosity increased with the increasing in concentration, but decreased with the increasing of temperature. Classification: Newtonian.	Akhavan Behabadi et al. [54]

ZnO+MWCNT in engine oil (0.125-1.0 vol.%)	Rotation / Brookfield cone & plate Viscometer (5-55 °C)	Increment of 45% with increasing concentration. Decrement of 85% with increasing of temperature. Classification: Newtonian.	Asadi and Asadi [55]
MgO+MWCNT in EG (0-1.0 vol.%)	Rotation / Brookfield Viscometer (30-60 °C)	Viscosity increased by 168% with increasing concentration. However, viscosity is decreased with the increasing of temperature. Classification: Newtonian.	Soltani and Akbari [56]
TiO_2+CuO+C in EG (0.5-2.0 vol.%)	Rotation / Physica MCR302 Rheometer (30-60 °C)	Viscosity increased with the increased of concentration. Maximum enhancement (80%) at ϕ = 2.0%. Classification: Newtonian.	Akilu et al. [57]
TiO_2+SiO_2 in W/EG (0.5-3.0 vol.%)	Rotational spindle / Brookfield Rheometer (30-80 °C)	Viscosity increased with increasing concentration but decreased with increasing temperature. Maximum enhancement (62.5%) at ϕ = 3.0%. Classification: Newtonian.	Nabil et al. [30]
Fe_3O_4+CNT Fe_3O_4 (0.1-0.9 vol.%) CNT (0-1.35 vol.%)	Rotation / Physica MCR300 (25-55 °C)	Viscosity increased with the increasing ϕ of CNT or Fe_3O_4 and decreasing with the increasing of temperature. Viscosity decreased with the increment in shear rate. Classification: non-Newtonian.	Shahsavar and Bahiraei [58]

Density and specific heat

The evaluation of any thermal systems with utilization of nanofluids requires precise particulars on thermo-physical properties. However, the research work for the investigation on the density and specific heat of nanofluids is limited in the printed matter and digital sources when compared to the evaluation on thermal conductivity and dynamic viscosity. Hence, only few important studies are presented in this section.

Density can be defined as a quantity of the mass of a substance per unit volume. Adding nanoparticles into the base fluid would enhance the density of mixture since the density of solid is greater than the liquids. The density of nanofluids is also proportional to the volume ratio of the solid (nanoparticle) and liquid (base fluid) in the system [59]. The density of nanofluids can be estimated by using conventional mixture relations. The equations are given by Eqs. (1) and (2) and used for the estimation of single nanofluids and hybrid nanofluids, respectively. Both equations were used by various studies in the literature [60-63].

The density mixture relation for single nanofluids is given by Equation (1).

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_{bf} \tag{1}$$

The density mixture relation for hybrid nanofluids is expressed by Equation (2). The subscripts of *bf*, *nf*, *hnf*, p_1 and p_2 represent base fluid, nanofluids, hybrid nanofluids, nanoparticle type 1 and nanoparticle type 2, respectively.

$$\rho_{hnf} = (\varphi\rho)_{p_1} + (\varphi\rho)_{p_2} + (1-\varphi)\rho_{bf} \tag{2}$$

Sommers and Yerkes [60] measured the density of Al_2O_3/propanol nanofluids by using two methods. They used hydrometer in the first method. Meanwhile, in the second method, they evaluated the density using simple calculations from the conventional density equation by measuring volume and weight of the fluid sample. The data undertaken from both methods were compared with the estimated density by using the mixing theory from Eq. (1). They observed a small difference with less than 5% deviation for measurements up to 5% weight concentration. Later, Ho et al. [61] investigated the density of Al_2O_3/water nanofluids for a wide range of concentration and temperature of 0 to 4% and 10 to 40 °C, respectively. From their measurements, the density of the nanofluids agreed well with the estimated values from the mixing theory. Similarly, Heyhat et al. [62] observed that the density measurement for Al_2O_3/water nanofluids with 0.1 to 2.0% volume concentration and 20 to 60 °C temperature were found to be in good agreement with the mixing theory. In another paper, Nabati Shoghl et al. [63] reported the density of five types of water based nanofluids namely Al_2O_3/water, CuO/water, MgO/water, TiO_2/water and ZnO/water for mass concentrations of 0.01 to 2.0%. The density of different nanofluids was compared with the estimation density by using the mixture relation. The findings showed that the density can be predicted by the mixture relation. The nanofluids density increased with increasing concentration however decreased when temperature increased. A mixture of heat capacities of solid and liquid phases when the phases are in thermal equilibrium is known as nanofluid specific heat [64]. The specific heat of nanofluids is smaller than the base fluid. This implies that the heat energy required is lesser for nanofluids at the same temperature increment compared to the base fluids [59]. The specific heat is estimated using thermal equilibrium condition as given in Equation (3) for single nanofluids. The specific heat of nanofluids requires the constituent's material densities, specific heat and volume concentration. The specific heat of hybrid nanofluids was derived from Equation (3). It consists of two types of nanoparticles and presented by Equation (4). Equations (3) and (4) were used in various studies [44, 65-68]. However, some researchers developed specific heat empirical model for their respective nanoparticle types, sizes, concentrations and temperatures [69-71]. The specific heat of single nanofluids is expressed by Equation (3).

$$C_{nf} = \frac{(1-\varphi)(\rho C)_{bf} + \varphi(\rho C)_p}{(1-\varphi)\rho_{bf} + \varphi\rho_p} \tag{3}$$

The specific heat of hybrid nanofluids is given by Equation (4). The subscript of *bf*, *nf*, *hnf*, p_1 and p_2 represent base fluid, nanofluids, hybrid nanofluids, nanoparticle type 1 and nanoparticle type 2, respectively.

$$C_{hnf} = \frac{(1-\varphi)(\rho C)_{bf} + (\varphi\rho C)_{p_1} + (\varphi\rho C)_{p_2}}{\rho_{hnf}} \tag{4}$$

Zhou and Ni [65] measured the specific heat of Al_2O_3/water nanofluids at concentrations of 0 to 21.7% by using differential scanning calorimeter. The results indicated that the specific heat of the nanofluids decreased gradually with increasing nanoparticle concentration. Their results also showed a good agreement with the prediction from the thermal equilibrium model of Eq. (3). O'Hanley et al. [66] studied the specific heat for Al_2O_3/water, CuO/water and SiO_2/water nanofluids. They reported that the specific heat increased with temperature but decreased with concentration. Their results were found to be in excellent agreement with the thermal equilibrium model. Barbés et al. [67] conducted a study on specific heat of Al_2O_3/water and Al_2O_3/EG nanofluids at temperatures of 25 to 65 °C using a micro calorimeter. The results for both nanofluids were reported to be in agreement with the observation undertaken by Zhou and Ni [65]. The specific heat decreased with increasing concentration. Similarly, the measured specific heat was compared with the prediction by using the thermal equilibrium model and found to be in good agreement. On the other hand, Equation (4) was used by Madhesh et al. [44] and Nuim Labib et al. [68] to estimate the specific heat of their Cu+TiO_2/water and Al_2O_3+CNT/water hybrid nanofluids, respectively. Table 3 summarized the measurement for density and specific heat of oxide nanofluids.

Table 3. Summary of density and specific heat measurements for oxide nanofluids.

Nanofluids (Range of concentration)	**Measurement method / Instrument (Temperature)**	**Significance findings**	**References**
		Density	
Al_2O_3 in propanol (up to 5 wt.%)	i. Hydrometer ii. Measured mass/volume (Room temperature)	A difference of less than 5% was observed for concentration up to 5 wt.%, compared to mixing theory relation.	Sommers and Yerkes [60]
Al_2O_3 in water (0-4.0 vol.%)	Density meter (10-40 °C)	The measured density in good agreement with mixing theory relation.	Ho et al. [61]
Al_2O_3 in water (0.1-2.0 vol.%)	Stabinger Viscometer (20-60 °C)	The measured density in good agreement with mixing theory relation.	Heyhat et al. [62]
Al_2O_3, CuO, MgO, TiO_2, ZnO in water (0.01-2.0 wt.%)	Density meter (30 and 40 °C)	Density can be predicted by the mixture theory relation. The nanofluids density were also increased with increasing of concentration and decreased with increasing of temperature.	Nabati Shoghl et al. [63]
		Specific heat	
Al_2O_3 in water (0-21.7 vol.%)	Differential scanning calorimeter (25-40 °C)	Specific heat declines gradually as the nanoparticle concentration increases.	Zhou and Ni [65]
Al_2O_3, CuO, SiO_2 in water (5-50 wt.%)	Differential scanning calorimeter (35, 45, 55 °C)	Specific heat increased with temperature but decreased with concentration.	O'Hanley et al. [66]
Al_2O_3 in water (3.7-9.3 vol.%) / Al_2O_3 in EG (1.0-8.0 vol.%)	Microcalorimeter (25-65 °C)	Specific heat decreased with increasing of concentration.	Barbés et al. [67]
Al_2O_3, CuO, SiO_2, TiO_2 (0.01-4.0 vol.%)	$20 < T < 50$ °C $15 < d_p < 50$ nm	$C_{p_r} = 0.8429\left(1+\frac{T_{nf}}{50}\right)^{-0.3037}\left(1+\frac{d_p}{50}\right)^{0.4167}\left(1+\frac{\phi}{100}\right)^{2.272}$	Sekhar and Sharma [69]

In thermo-physical properties evaluation, the nanofluids were proven to show better thermal properties and high enhancements in thermal conductivity with acceptable viscosity increments. The properties of the oxide nanofluids were measured for temperatures ranging from 10 to 90 °C. Most studies in literature used transient hot wire methods to measure thermal conductivity and rotational spindle for viscosity measurements of oxide nanofluids. The oxide nanofluids and its hybrid were observed to display Newtonian behaviour at volume concentrations of less than 8.0% for single nanofluids and up to 2.0% volume concentration for hybrid nanofluids. The evaluation of thermal conductivity and dynamic viscosity mostly were determined through experimental measurements. The mixture relations for single and hybrid nanofluids were used by various researchers to estimate specific heat and density of nanofluids. The equations were used in the analysis of the present study to estimate the specific heat and density of the hybrid nanofluids. Figure 1 shows the variation of thermal conductivity enhancement for several type of metal oxide nanofluids. Maximum 40% enhancement of the thermal conductivity of oxide nanofluids was achieved for the case of CuO/water nanofluids in comparison with base fluids [35].

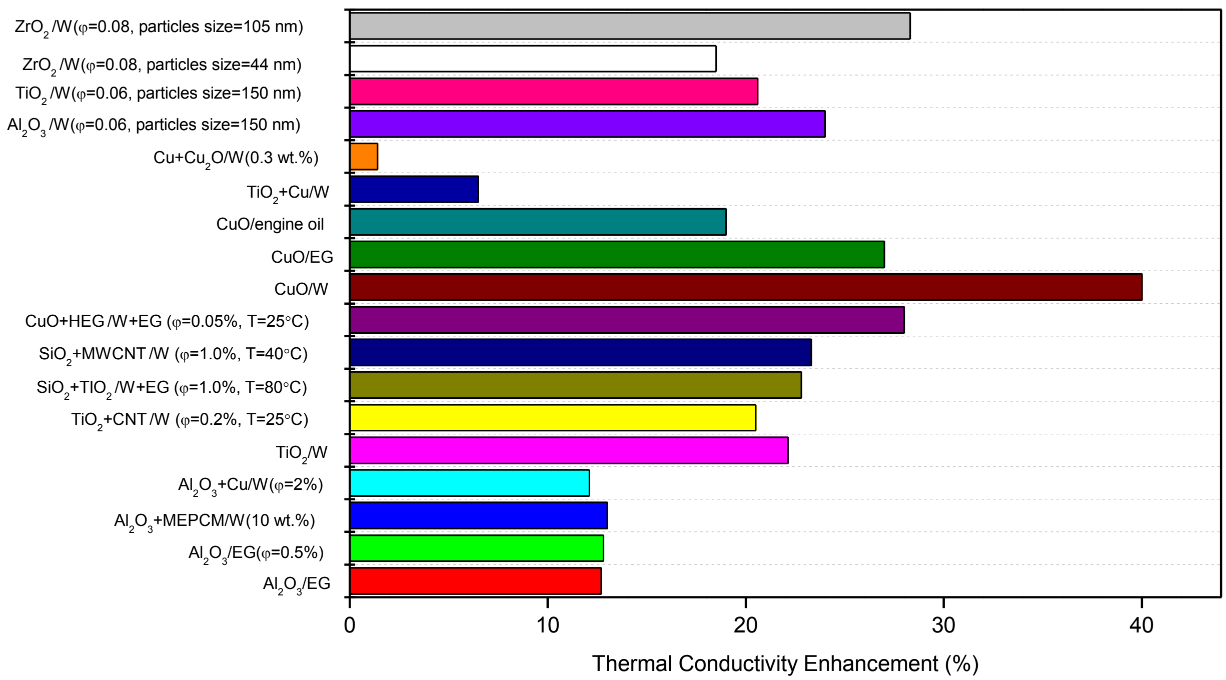

Figure 1. The variation of thermal conductivity enhancement for different type of metal oxide nanofluids.

HEAT TRANSFER PERFORMANCE OF OXIDE NANOFLUIDS

The nanofluids were proven to enhance thermal properties by different studies and summarized in the previous section. Furthermore, various studies were undertaken either through experiment or numerically in order to investigate the heat transfer performance of oxide nanofluids. Forced convection heat transfer is one of the common methods to investigate the nanofluid behaviour on the heat transfer performance. The heat transfer enhancement can be achieved by increasing either the surface area where heat transfer occurred or the heat transfer coefficient between fluid and solid surface. At this condition, it will allow a high rate of heat transfer in small volumes [72]. The nanofluids are believed to have potential as a cooling agent or heat transfer fluids. The fundamental forced convection heat transfer observation of nanofluids is important as a benchmark for various diverse industries cooling applications such as manufacturing, solid-state lighting, power generation, micro-manufacturing, transportation, chemical and metallurgical sectors, thermal therapy for cancer treatment, ventilation, heating, cooling and air-conditioning as well as renewable energy. The following section describes numerous important studies of heat transfer for different types of oxide nanofluids and summarized in Table 4. The reviews considered the investigation of oxide nanofluids by experimental or numerical works with some important parameters namely, flow region, nanofluid properties, conditions, geometric designs and inserts in which significantly affected the overall heat transfer performance. Figure 2 presents the variation of heat transfer performance for various types of metal oxide nanofluids in a plain tube. In the literature, the heat transfer performance was improved for up to 60% with the use of Fe_3O_4/water nanofluids in the heat transfer system under laminar flow condition [73].

Table 4. Summary of forced convection heat transfer with different test section for oxide nanofluids.

Nanofluids (Range of concentration)	**Types of study / Test section / Range of Re**	**Enhancement in *Nu,h, f* / Significant findings**	**References**
Al_2O_3 in water (0-2.5 vol.%)	Experiment / Plain tube with butterfly tube inserts / *Re* (750-8,500)	Enhancement in *Nu* (345%) at ϕ = 0.027% and *Re* = 1,500 with insert. Further enhancement in *Nu* at ϕ = 2.5% with insert Increment in *f* (2.6%)	Azari and Derakhshandeh [74]
Al_2O_3 in water (0-6.0 vol.%)	Numerical / Circular tube / *Re* (5,000-18,000)	Optimal cross section area increased as increasing the *Re*	Mwesigye and Huan [75]
Al_2O_3 in water (0-4.0 vol.%)	Numerical / Mini-channel with ribbed upper and lower walls (triangular, rectangular and trapezoidal) / *Re* (20,000-60,000)	Heat transfer rate increased with increasing of ϕ and *Re* however with additional pumping power. The thermal performance of triangular rib is higher than rectangular and trapezoidal ribs.	Andreozzi et al. [76]
Al_2O_3 in water (0-0.1 vol.%)	Numerical / Mini-channel	Compared to the shear-induced diffusion and viscosity gradient-induced diffusion, Brownian diffusion and thermophoresis are considered more significant mechanisms based on their impacts on volume fraction distribution of nanofluids.	Yang et al. [77]
Al_2O_3 in water (2-10 wt.%)	Experiment / Circular tube / *Re* (188-2,095)	Heat transfer effectiveness increases with the decreasing of parameter l^*_h. Higher average heat transfer effectiveness and figure of merit (FOM) are noted for cases with higher inlet fluid temperature (45.5 - 50.5 °C).	Ho et al. [78]
Al_2O_3 in water/EG (0.2-1.0 vol.%)	Experiment / Circular tube / *Re* (3,000-25,000)	Enhancement in *Nu* (24.6%) for the base ratio W/EG (60:40), ϕ = 1.0% and 70 °C. Increment of *f* is slightly increased with increment of ϕ.	Azmi et al. [79]
TiO_2 in water/EG (0.5-1.5 vol.%)	Experiment / Circular tube / *Re* (3,000-22,000)	Enhancement in *Nu* (22.8% and 28.9% at 50 °C and 70 °C, respectively) and significantly for	Khdher et al. [80]

		higher ϕ. Increment in f (1.1 times the base fluid).	
TiO_2 in water (0.1-0.5 vol.%)	Experimental & numerical / Helical coil pipe (5 curvature ratio) / *Re* (3,000-18,000)	Enhancement in *Nu* (30%) at ϕ = 0.5%, *h* increased when the Dean number (curvature ratio) is increasing at fixed *Re*. Increment in *f* (higher *f* with helical coil when compared to base fluid)	Mahmoudi et al. [81]
TiO_2 in water (0.1-0.5 wt.%)	Experimental & numerical / Corrugated tube / *Re* (<12,000)	Enhancement in *h* (53.95% and 16.06% for corrugated tube and circular tube). Maximum performance index (1.507)	Qi et al. [82]
SiO_2 and TiO_2 in water (0.5-3.0 vol.%)	Experiment / Circular tube / *Re* (5,000-25,000)	Enhancement in *h* (26%) for TiO_2/water at ϕ = 1.0% and (33%) for SiO_2/water at ϕ = 3.0%	Azmi et al. [83]
CuO in oil (0.5-1.5 wt.%)	Experiment / Circular & microfin tube / *Re* (110-730)	Enhancement in *h* (16% and 22% for circular tube and microfin tube, respectively). Performance index (1.16) for circular tube at ϕ = 1.5%, (1.44) for microfin tube at ϕ=1.5%	Hekmatipour et al. [84]
CuO in water (0-4.0 vol.%) (shape: spherical, platelet, cylinder and brick)	Numerical / Semi annulus / *Re* (100-600) Darcy number (0.01-100) Hartmann number (0-50)	*Nu* enhanced with increasing of ϕ, *Re* and Darcy number. The platelet shape has the greatest heat transfer rate among other shape.	Sheikholeslami and Bhatti [85]
GO in water (0-0.2 vol.%)	Experiment / Tube in subsonic wind tunnel / *Re* (3,800-21,500)	Enhancement in *Nu* (51.4%) compared to pure water. Increment in *f* (21%). Enhancement in *h* (42.2%).	Ranjbarzadeh et al. [86]
ZrO_2 in water (4.0 vol.%)	Experiment / Tubes (smooth tube, tube+annular knurling, tube+spherical protrusions) / Re (3,000-8,000)	Enhancement in *h* (+35%) for size of 44 nm, (-20%) for size of 105 nm. Tube with annular knurling and protrusions showed lower thermal hydraulic efficiency compared to smooth tube.	Minakov et al. [88]
Fe_3O_4 in water (4.0 vol.%)	Numerical / *Re* (10-600), Hartmann number (0-10),	*Nu* is increasing with *Re*, ϕ and magnetic number. However, the *Nu* is decreasing with the Hartmann number.	Sheikholeslami et al. [89]

	Magnetic number (0-10)		
Fe_3O_4 in water (0.1-1.0 vol.%)	Experiment / *Re* (<400), Hartmann number (33.4×10^{-4}-136.6×10^{-4})	Enhancement in *h* (+60%) with increasing ϕ without external magnetic field, (-25%) with increasing ϕ in the presence of magnetic field.	Hatami et al. [73]

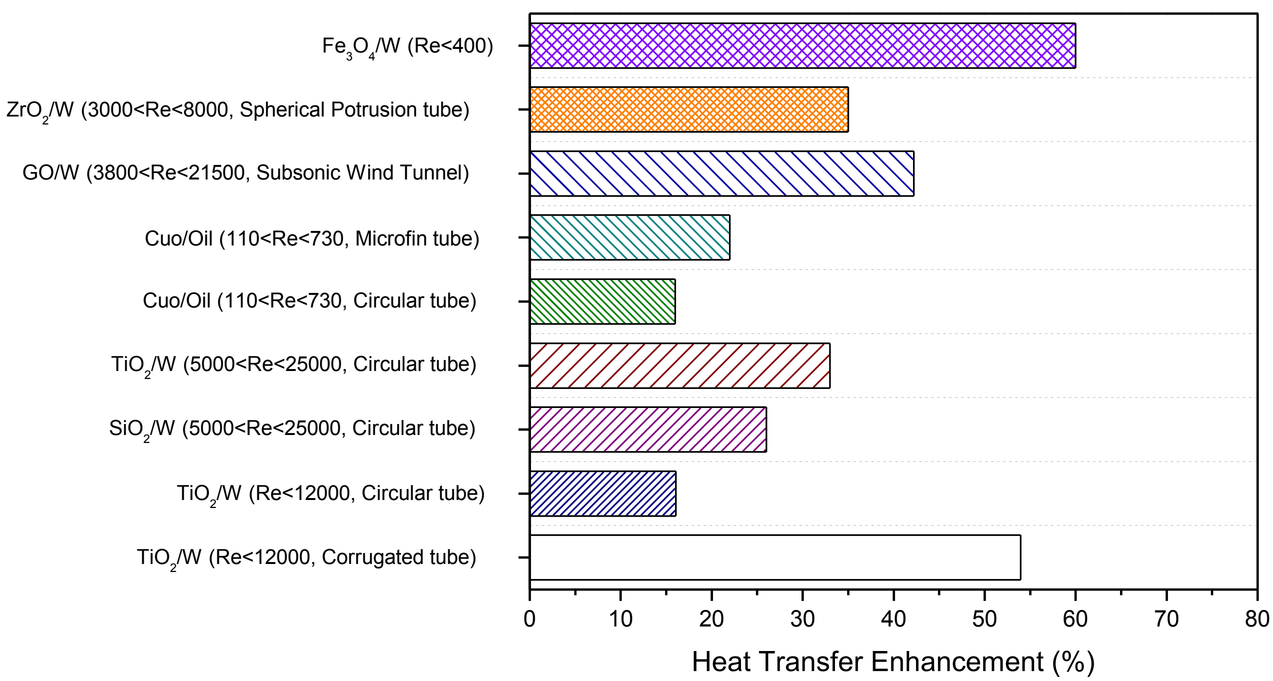

Figure 2. The variation of heat transfer augmentation for various types of metal oxide nanofluids in a plain tube.

Aluminum Oxide Nanofluids

Azari and Derakhshandeh [74] conducted a study with Al_2O_3/water at concentrations of up to 2.5% and Reynolds number of 750 to 8,500. The plain tube was equipped with butterfly tube inserts with inclined angle of 90°. They found that the nanofluid friction factor with inserts increased by an average of 2.6% relative to the plain tube. The Nusselt number enhancement was observed up to 345% for concentration of 0.027% and Reynolds number of 1,500 with insert when compared to the plain tube. Another 2.5% increment was obtained for Nusselt number with butterfly tube insert. Furthermore, Mwesigye and Huan [75] conducted a numerical study on thermodynamics analysis for turbulent forced convection in a circular tube with Al_2O_3/water nanofluids. The study was conducted for different cross-sectional areas, concentrations and Reynolds number at a wide range of 2.5×10^{-6} to 0.05 m^2, 0 to 6.0% and 5,000 to 18,000, respectively. The results showed that the optimal cross-sectional area increased with increasing Reynolds number.

Andreozzi et al. [76] studied the numerical investigation on forced convection in mini-channel using Al_2O_3/water nanofluids. The channel was designed with ribbed upper and lower walls. The experiment was conducted for 0 to 4% volume concentrations of nanofluids, Reynolds number ranges from 20,000 to 60,000 and heated under a constant heat flux condition. The effects of three rib geometries arrangement namely triangular, rectangular and trapezoidal were also investigated in their study. The results indicated the dependence of heat transfer rate on nanofluid concentrations and Reynolds number where it increases when the previously mentioned variables increase; however, there is a drawback with high pumping power requirements. The best thermal performance was observed with triangular rib compared to rectangular and trapezoidal ribs. In another paper, Yang et al. [77] studied forced convection in mini-channels with Al_2O_3/water nanofluids. The numerical study was conducted for nanofluid concentrations of less than 0.1% using Runge-Kutta-Gill method. The results were analyzed by investigating the effect of different mechanisms on volume fraction distribution of nanofluids. Their findings showed that the Brownian diffusion and thermophoresis were reported as more dominant mechanisms than shear-induced diffusion and viscosity gradient-induced diffusion.

Ho et al. [78] conducted an experimental study on forced convection effectiveness of Al_2O_3/water nanofluids in a circular tube. The study used Al_2O_3/water nanofluids with 2 to 10% weight concentrations, Reynolds number of 188 to 2,095 and inlet temperature of 24.5 to 50.5 °C. Based on the results, they observed that the average heat transfer effectiveness increased with decreasing parameter l^*_h. In addition, the improvement in average heat transfer effectiveness and figure of merit (FOM) were recorded for cases with high inlet fluid temperature from 45.5 to 50.5 °C. In another paper, Azmi et al. [79] conducted an experimental investigation of forced convection with Al_2O_3 nanoparticles for 0.2 to 1.0% volume concentration and three different ratios of water to EG mixture namely 60:40, 50:50 and 40:60. The experiment took place at different working temperatures of 30 to 70 °C and turbulent Reynolds number from 3,000 to 25,000. The results indicated that the Al_2O_3 nanofluids with 60:40 (W/EG) based ratio provided the highest heat transfer enhancement up to 24.6% for 1.0% volume concentration and 70 °C working temperature. A slight increase in friction factor was observed with increasing volume concentration.

Titanium Dioxide Nanofluids

Khdher et al. [80] carried out an experimental study of forced convection heat transfer for TiO_2 nanoparticles in W/EG mixture. The nanofluids was tested in a circular tube for volume concentrations of 0.5 to 1.5% and different working temperatures of 50 and 70 °C. The results showed that the enhancements of Nusselt number were reported up to 22.8% and 28.9% for temperatures of 50 and 70 °C, respectively. The friction factor increased approximately 1.1 times higher than the base fluid. Another experimental and numerical study was undertaken by Mahmoudi et al. [81] for TiO_2/water nanofluids at volume concentrations of 0.1 to 0.5%. The test section was equipped with helical coils and five curvature ratios. The results were obtained with 30% heat transfer enhancements for 0.5% volume concentration of nanofluids. The heat transfer increased with increasing Dean number (curvature ratio) at a constant Reynolds number. However, the use of a helical coil resulted in higher friction factors when compared to the base fluid.

Later, Qi et al. [82] studied the heat transfer characteristics for corrugated tube by experimental and numerical investigations. The TiO_2/water nanofluids was tested with weight concentrations of 0.1 to 0.5% in circular and corrugated tubes for Reynolds number of less than 12,000. They reported that the maximum enhancement of heat transfer for corrugated tube and circular tube up to 53.95% and 16.06%, respectively. In this case, the nanoparticle concentration in their study caused minimum additional resistance loss to the system. The maximum comprehensive performance index (ratio of Nusselt number to friction factor) was obtained up to 1.507. In another study, Azmi et al. [83] conducted a comparative experimental study for SiO_2/water and TiO_2/water nanofluids to investigate the convective heat transfer performance in a circular tube. The experiments were performed at turbulent Reynolds number of 5,000 to 25,000 and 0.5 to 3.0% volume concentrations for a constant working temperature of 30 °C. According to the results, they reported 26% maximum enhancement of heat transfer coefficient for TiO_2/water nanofluids at 1.0% volume concentration. Meanwhile, heat transfer enhancement for SiO_2/water nanofluids was achieved up to 33% for 3.0% volume concentration.

Copper (II) Oxide Nanofluids

Hekmatipour et al. [84] conducted a study on convective heat transfer performance in a horizontal tube with CuO nanoparticles dispersed in heat transfer oil. The nanofluids were prepared for weight concentrations of 0.5 to 1.5%. It was tested under the laminar flow with Reynolds number of 110 to 730. The results reported an enhancement up to 16% of the heat transfer for circular tubes and 22% for microfin tubes by using CuO/oil nanofluids. In addition, the performance index was found to be more than unity for the majority of the results. The performance index for 1.5% weight concentration were obtained up to 1.16 and 1.44 for circular tube and microfin tube, respectively. Furthermore, Sheikholeslami and Bhatti [85] investigated a numerical study on forced convection of CuO/water nanofluids with the presence of uniform magnetic field. They tested the nanofluids with four different shapes of nanoparticles namely spherical, platelet, cylinder and brick. The experiment was undertaken for Reynolds number of 100 to 600, Darcy number of 0.01 to 100, Hartmann number of 0 to 50 and up to 4.0% concentration. The Nusselt number was enhanced with increasing nanoparticle concentrations, Reynolds number and Darcy number. Lastly, the platelet shape of nanoparticles recorded the highest heat transfer rate when compared to other shapes.

Other types of Oxide Nanofluids

Ranjbarzadeh et al. [86] examined the effects of graphene oxide/water nanofluids on convective heat transfer for a tube under air-cross flow. The experiment was performed for a wide range of Reynolds number from 3,800 to 21,500 and up to 0.2% volume concentration. The free air flow was generated by a subsonic wind tunnel. In their study, the average Nusselt number for nanofluids was enhanced up to 51.4% better than pure water. The friction factor increased with increasing nanofluid concentration with 21% maximum increment. This is due to the increase with the viscosity of graphene oxide/water nanofluids. The heat transfer performance also was increased up to 42.2%. Similar observation also was found by Zainal Abidin et al. [87] and Abdullah et al. [3] however for different types of nanofluids. Furthermore, Minakov et al. [88] evaluated the heat transfer performance of ZrO_2/water nanofluids for 4.0% volume concentrations with different nanoparticle sizes of 44 and 105 nm. The experiment was undertaken for Reynolds number of 3,000 to 8,000 and different types of tubes viz. smooth tube, tube with annular knurling and tube with spherical protrusions. Their findings showed that ZrO_2 nanoparticles with 44 nm improved the heat transfer by 35% when compared to the base fluid. Conversely, the ZrO_2 nanoparticles with 105 nm decreased the heat transfer performance by 20%. Then, the tube with annular knurling and protrusions experienced lower thermal hydraulic efficiency when compared to smooth tubes. Hence, the use of ZrO_2/water nanofluids in channels with artificial enhancers appeared to be less effective in terms of thermal hydraulic efficiency.

Sheikholeslami et al. [89] conducted a numerical study on convective heat transfer under the influence of a magnetic field. They utilized Fe_3O_4/water nanofluids with 4.0% volume concentration. The nanofluids were tested for a wide range of Reynolds number from 10 to 600 and up to 10 for the Hartmann number and magnetic number. The results showed that the Nusselt number improved with increasing Reynolds number, nanofluid concentrations and magnetic number. On the contrary, the Nusselt number decreased with increasing Hartmann number. In another study, Hatami et al. [73] investigated the heat transfer performance of Fe_3O_4/water nanofluids under a magnetic field. The experiment was conducted for laminar flow with Reynolds number of less than 400, Hartmann number of 33.4×10^{-4} to 136.6×10^{-4} and nanofluid concentrations of 0.1 to 1.0%. By increasing the volume concentration, this will cause a 25% reduction in convective heat transfer coefficient with the presence of a magnetic field. However, the increment of nanoparticle loading enhanced the heat transfer for more than 60% without the existence of an external magnetic field.

CONCLUSIONS

In the present paper, a comprehensive summary on thermo-physical properties and heat transfer application of oxide nanofluids was reviewed. The oxide nanofluids are widely used in numerous engineering applications. The oxide nanofluids is one of the favorable single type nanofluids being used in preparations of hybrid or composite nanofluids. Al_2O_3, TiO_2, SiO_2 and CuO nanofluids are mostly used in heat transfer application. Meanwhile other types such as Fe_3O_4, ZnO and MgO nanofluids are also implemented, however with only a small number of studies reported. In thermo-physical properties evaluation, the oxide nanofluids were proven to perform better thermal properties and high enhancements in thermal conductivity with acceptable viscosity increments. In the literature, the thermal conductivity of oxide nanofluids was enhanced up to 40% better than the base fluids. Furthermore, the forced convection studies using oxide nanoparticles for single and hybrid nanofluids showed significant improvements in heat transfer performance. It was reported in the literature with the heat transfer enhancement up to 60% with the use of oxide nanofluids in the heat transfer system. In addition, some studies stated that the drawback with friction factor and pressure drop by utilizing the nanofluids in heat transfer system is insignificant. On this basis, we conclude that nanofluids are recommended in heat transfer system.

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