RECENT PROGRESS ON PREPARATION, PROPERTIES AND APPLICATIONS OF NANOFLUIDS

J.E. SILVA YUMI†, T.J. MORENO‡ and G.C. CHANGO‡

† *Faculty of Science, Escuela Superior Politécnica de Chimborazo, Riobamba, EC060155, Ecuador.*
jorge.silvay@espoch.edu.ec
‡ *Faculty of Mechanics, Escuela Superior Politécnica de Chimborazo, Riobamba, EC060155, Ecuador.*
telmomoreno@hotmail.com, gabycris018@gmail.com

***Abstract*— Nanofluids are defined as base fluids containing nanoparticles in suspension, the nanoparticles can be oxides, aluminum oxide, silicon oxide, titanium oxide, metallic nanoparticles, carbon nanotubes, graphene, etc. Nanofluids can be synthesized by two methods and it is necessary to control some of the characteristics such as stability, thermal conductivity, viscosity, etc. Although the presence of nanoparticles allows generating or improving the characteristic properties of nanofluids, such as their thermal conductivity, it is important to differentiate between the behavior of simple nanofluids and hybrid nanofluids, since in some cases they present different behaviors. Nanofluids have multiple applications in automotive, biomedicine, as coolants, etc. This article reviews nanofluids and their types: nanolubricants, nanorefrigeramts, simple nanofluids, hybrid nanofluids, the nanoparticles used to obtain them, as well as the properties and variables considered in their elaboration and finally some of the applications and uses. For this purpose, articles have been searched and compiled using the keywords: nanofluids, nanorefrigerants, nanolubricants in the Science direct database. It is hoped that the information analyzed will be useful for those entering the field of nanofluids.**

***Keywords*— nanofluids, hybrid nanofluids, nanoparticles, nanorefrigerant, energy, properties.**

I. INTRODUCTION

Nanofluids are defined as base fluids containing dispersed nanoparticles (Abbas *et al*., 2020), which can be oxides, metallic nanoparticles, carbon materials, such as nanotubes, graphene, graphene oxide, etc., which are currently used for their benefits in heat transfer for engineering applications.

Concepts such as nanolubricants have been derived around nanofluids, which correspond to lubricants produced by the dispersion of nanoparticles in conventional lubricating oils (Sanukrishna and Jose Prakash, 2018), nanorefrigerants, which are also stable mixtures of nanoparticles and refrigerants focused mainly on improving the transfer characteristics of heat (Sanukrishna *et al*., 2018).

Currently, society is inclined to an efficient use of energy as well as to a maximize energy savings in favor of the environment, nanorefrigerants constitute a timely alternative (Azmi *et al*., 2017) since they allow to improve energy efficiency in some way.

Nanofluids have a wide range of applications in heat exchangers, lubricants, refrigerants, solar collectors, etc., however there are a number of variables that must be considered in the synthesis of nanofluids for their optimal functioning, variables such as pH level, suspension stability, density, viscosity, surface tension, among others.

In this article, a review of nanofluids, the nanoparticles used to obtain them, as well as the properties and variables considered in their elaboration and finally some of the applications and uses is carried out.

In the last years did not puplish a review from synthesis to applications of nanofluids. There are some review articles but they are focused in specialized topics of nanofluids like: the thermal conductivity (Li *et al*., 2021) heat transfer (Ali and Salam, 2020; Muneeshwaran *et al*., 2021), stability (Ali and Salam, 2020; Chakraborty and Panigrahi, 2020).

This review article aims to be an article oriented to those who enter the world of nanofluids but do not know much about the subject, for which it provides a review from the concept, types of nanofluids, types of nano-materials and base fluids used in obtaining them, as well as a brief discussion of some of its properties and finally the applications.

II. METODOLOGY

The review was carried out during the 2019–2022 period, the ScienceDirect database was used to search for review and research articles using the keywords: nanofluids, nanorefrigerants, nanolubricants, hybrid nanofluids, review nanofluids, review nanorefrigerants, review nanolubricants, review hybrid nanofluids.

101 articles have been selected from which the information presented in this review has been synthesized and systematized. It begins with the definition of hybrid nanofluids and nanofluids, then the synthesis methods are presented, as well as the nanoparticles and base fluids used to obtain them, finally the evaluated properties of nanofluids and some of the applications in different areas are mentioned.

III. NANOFLUIDS

Nanofluids are stable and uniform suspensions consisting of so-called base fluids that contain dispersed nanoparticles. Within the nanoparticles used are oxides of: aluminum (Sanukrishna and Jose Prakash, 2018) copper, titanium, zirconium, tungsten, zinc, silicon (Che Sidik *et al*., 2017b), metallic nanoparticles of: copper, silver, gold (Li *et al*., 2019), iron (Sarkar and Kumar Ghosh, 2022), carbon nanotubes (Eltaweel and Abdel-Rehim, 2019; Kim *et al*., 2018), functionalized graphene (Paul *et al*., 2019) reduced graphene oxide (Xu *et al*., 2019) carbon nanofibers (Said *et al*., 2020), gallium oxide (El-Salamony and Morsi, 2018), zinc oxide (Kumar *et al.*, 2018) among others.

Nanofluids show significantly better thermal properties than base fluids, nanoparticles help improve thermal conductivity (Said and Saidur, 2017), the heat transfer coefficient (Xu *et al*., 2019) of the nanofluid compared to the base fluid (Liu *et al*., 2018), this improvement may be due at the high surface-volume ratio of nanomaterials (Al-Waeli *et al*., 2019b; Mashali *et al*., 2019). If the concentration of nanoparticles in nanofluid is varied, is possible adjust the thermo-physical properties of nanofluid according to our requirement (Kumar and Sarviya, 2021). The disadvantage of nanofluids is that they exhibit high viscosities due to the presence of nanoparticles and a higher pumping power is required.

Nanofluids have found relevant applications in heat transfer processes (Usri *et al*., 2015), have been used in solar collectors (Eltaweel and Abdel-Rehim, 2019; Xu *et al*., 2019), plate heat exchangers, thermal photovoltaic systems (Al-Waeli *et al*., 2019b), air conditioning systems, in heat transfer (Ganvir *et al*., 2017), thermal conductivity (Tawfik, 2017), electronic chip cooling, car engines (such as lubricants and coolants), refrigerators and nuclear power plants (such as coolants for nuclear fuel rods) (Chakraborty *et al*., 2019).

A. Nanolubricants

Nanolubricants correspond to lubricants produced by the dispersion of nanoparticles in conventional lubricating oils (Sanukrishna and Jose Prakash, 2018). Nanolubricants also are employed in heat transfer devices to improve thermal qualities such as conductivity, viscosity, and thermal diffusivity (Ahmed and Ahamed, 2022) to reduce friction, enhance lubrication, and reduce wear of interacting surfaces that are in relative motion.

B. Nanorefrigerants

Nanorefrigerants are newly invented refrigerants with promising thermal, rheological, and tribological properties. Are also stable mixtures of nanoparticles and refrigerants focused mainly on improving the transfer characteristics of heat (Sanukrishna *et al*., 2018). Nanoparticles such as aluminum oxide, copper oxide, titanium dioxide, silicon dioxide, copper, titanium, aluminum, and diamonds in water, glycol, oils, and conventional refrigerants (Kasaeian *et al*., 2018)

Nanorefrigerants have some applications in diverse fields like refrigeration, heat pumps and air conditioning systems.

IV. HYDRID NANOFLUIDS

Hybrid nanofluids are a new class of nanofluids which contain two or even three different types of nanoparticles in a specific fluid (Che Sidik *et al*., 2017a), or a combination thereof.

As in simple nanofluids, different nanoparticles are used for their preparation (Ranga Babu *et al*., 2017), among the combinations of nanoparticles used, the following could be mentioned: Ag-MWCNT (silver-multi-walled carbon nanotubes) (Sun *et al*., 2019) SWCNT-MgO (single-walled carbon nanotubes – magnesium oxide), MWCNT-MgO, MWCNT- Fe_3O_4, Fe_3O_4-graphene, Al_2O_3-Cu, Al_2O_3-Ag, (Huminic and Huminic, 2018), Cu-TiO_2, (Sundar *et al*., 2017) iron oxide and fullerene nanoparticles (Cimbala *et al*., 2022), graphene oxide (GO)-silicon (Si) (Vărdaru *et al*., 2022).

Are ternary examples of nanofluids, $ZnFe_2O_4$-$MnZnFe_2O_4$-$NiZnFe_2O_4$-H_2O (Goud *et al*., 2022) and Al2O3–SiO_2–TiO_2 suspended in ethylene glycol base fluid (Abbasi *et al*., 2022).

Unlike nanofluids based on a single type of nanoparticles, hybrid nanofluids produce, in some cases, a greater improvement in heat transfer (Sundar et al., 2017) due to synergistic effect of nanoparticles.

However, heat transfer like thermal conductivity are affected by several factors such as particle size and volume fraction, working temperature of the fluid, and hybrid nanofluid viscosity (Hanafi *et al*., 2022)

V. NANOFLUIDS PREPARATION

Nanofluids can be prepared using two methods: The one-step method and the two-step method (Dhinesh Kumar and Valan Arasu, 2018; Leong *et al*., 2017), regardless of the method, it is necessary to ensure that the nanoparticles are dispersed homogeneously, and that the nanofluid shows stabile characteristics and desired properties.

A. One-step method

The one-step method involves the synthesis and dispersion of nanoparticles in the base fluid in one step (Babar and Ali, 2019).

The disadvantages of this method are the variability of the scale for industrial applications; is not suitable for mass production (Muneeshwaran *et al.*, 2021) and the only usability of low-pressure base liquids.

The chief advantage of this method is to control the size and size distribution of particles (Yang *et al*., 2020).

B. Two-step method

In this method, nanoparticles are synthesized by any of the approaches, be it bottom-up or top-down, nanoparticles are in the form of dry powder and they can later be dispersed in any base fluid (Babar and Ali, 2019). During dispersion of nanoparticles in base fluid, the Van der Waal forces could cause cluster formation of nanoparticles (Kumar and Sarviya, 2021), so is important use some chemical and physical methods like, ultrasonic vibration, acidity change, surfactant or generate surface charge on the nanoparticles in such a way that repulsion occurs by load avoiding agglomeration.

This technique is suitable where concentration of nanoparticles is up to 20% (Kumar and Sarviya, 2021).

B. Other new methods

Another method of nanofluid preparation is phase transfer (Yang *et al*., 2020).

VI. NANOPARTICLES USED FOR NANOFLUIDS

Among available particles that are used to obtain nanofluids are: aluminum oxides (Ho *et al*., 2019), diamond (Mashali *et al*., 2019) copper, titanium, zirconium, tungsten, zinc, silicon (Che Sidik *et al*., 2017b), metallic copper nanoparticles, silver (Kimpton *et al*., 2021), gold, carbon nanotubes, carbon nanofibers (Said *et al*., 2020), calcium oxide (Sunil *et al*., 2019), etc.

A. Oxides

Oxides are resistant to oxidation, they are chemically stable and the density of some is low, which allows them to be easily dispersed in base fluids, however they have a low thermal conductivity when compared to metals (Suganthi and Rajan, 2017).

Among the oxides used to obtain nanofluids, aluminum or alumina oxide (Al-Waeli *et al*., 2019a; Ho *et al*., 2019) can be mentioned due to its high thermal conductivity and low density, calcium oxide (Sunil *et al*., 2019), gallium oxide (El-Salamony and Morsi, 2018), titanium oxide (Murtadha *et al*., 2022), silicon dioxide (Afekare *et al*., 2020) iron oxides (Goharkhah *et al*., 2016) aluminum oxide, copper oxide, titanium dioxide (Khan *et al*., 2019), zirconium oxide, tungsten, zinc, silicon (Che Sidik *et al*., 2017b).

In the case of the use of iron oxide, magnetic nanofluids are obtained since the nanoparticles that make them correspond to magnetic nanoparticles and therefore this type of fluid responds to a magnetic field.

B. Metallic nanoparticles

Metals generally have higher thermal conductivity than fluids. Copper for example is the metal that has the highest thermal conductivity among the metal families (Hanafi *et al*., 2022), therefore the use of metallic nanoparticles in a fluid produces a good thermoconducting nanofluid (Eltaweel and Abdel-Rehim, 2019).

Among metallic nanoparticles, those of copper (Che Sidik *et al*., 2017b), silver (Che Sidik *et al*., 2017a; Li *et al*., 2019; Parametthanuwat *et al*., 2015), gold (Li *et al*., 2019) and iron (Sarkar and Kumar Ghosh, 2022), can be mentioned.

In the case of metallic silver particles, which have high thermal conductivity, its electrical conductivity can make it not so useful in some applications (Mashali *et al*., 2019).

C. Carbon materials

The use of carbon nanotubes (Che Sidik *et al*., 2017b; Eltaweel and Abdel-Rehim, 2019; Kim *et al*., 2018) multiwall carbon nanotubes (Sivalingam *et al*., 2022), carbon black, carbon nanopowder (Ueki *et al*., 2017) graphene (Yarmand *et al*., 2016), graphene oxide (Kanti *et al*., 2022) reduced graphene oxide (Xu *et al*., 2019), carbon nanofibers (Said *et al*., 2020), carbon quantum dots (Zhou *et al*., 2022), fullerenes (Cimbala *et al*., 2022) and even diamond nanoparticles have been evaluated due to their thermal, mechanical and electric properties (Mashali *et al*., 2019).

D. Nitrides and metal carbides

The use of SiC (Al-Waeli *et al*., 2019a;b), has been evaluated for its high thermal conductivity. Titanium Carbide (Abhilash *et al*., 2021), tungsten carbide (Roy *et al*., 2019). Transition metal nitrides like: TiN, ZrN, and HfN also has been evaluated due to their high optical absorption cross-section, which is associated to the localized surface plasmon resonances phenomenon, they reach thermal efficiency higher than 80% (Vital *et al*., 2021).

VII. BASED FLUIDS FOR NANOFLUIDS

Water, oil, alcohol and kerosene are some of the base liquids used to make nanofluids.

Water and glycols are the most studied base liquids, glycols such as ethylene glycol and propylene glycol have lower freezing points than water and are used alone or in mixture with water. Both ethylene glycol and propylene glycol (Al-Waeli *et al*., 2019b) have been generally used as they are readily available, reasonably affordable, and widely used as base fluids.

In addition to water and glycols, motor oil, kerosene, vegetable oil like: canola and extra virgin olive oils (Rahman *et al*., 2019) paraffin and mineral oil (Ahmed and Ahamed, 2022) are also used.

Conventional heat transfer fluids, such as water and oil have low thermal conductivity, which is an impairment to improving the efficiency of all heat exchangers (Al-Waeli *et al*., 2019a).

As an alternative to conventional lubricants, bio-lubricants have emerged since they are less toxic than mineral oils. The lubricating properties of bio-lubricants are slightly less than those of mineral oils and have poor oxidative stability that restricts their use at high temperatures, so the addition of nanoparticles improves the optical, physical (Mashali *et al*., 2019), thermal (Al-Waeli *et al*., 2019a), magnetics (Usri *et al*., 2015), electrical, chemical (Ganvir *et al*., 2017), antifoam, antifriction and antiwear properties (Sunil *et al*., 2019), rice bran oil (Sunil *et al*., 2019) is one of the base fluids used to obtain biodegradable lubricants.

VIII. PROPERTIES EVALUATED IN NANOFLUIDS

Thermal conductivity (Munyalo and Zhang, 2018; Suganthi and Rajan, 2017), viscosity (Bashirnezhad *et al*., 2016), density (Bhattacharya and Sharma, 2016), specific and latent heat (Shin and Banerjee, 2011; Zabalegui *et al*., 2014) are some of the thermophysical properties used to evaluate the usefulness of nanofluids in heat transfer processes. The factors that influence the thermophysical properties of nanofluids are: size, concentration, aggregate and shape of the nanoparticles used as the dispersed solid phase.

The properties of the base fluid, the interaction between the nanomaterial and the molecules of the base liquid, the surfactant used for the formulation, the dispersion and the pH also affect the behavior of the resulting nanofluid (see Fig. 1). The mono nanofluids,

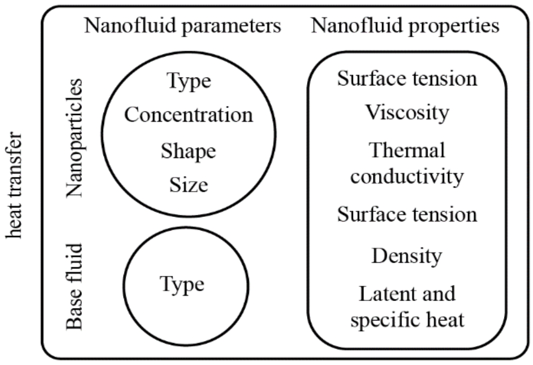

Figure 1 Relationship between parameters and properties of fluids, nanoparticles and nanofluids.

employing only single-type nanoparticles (metallic or nonmetallic), revealed the stable thermophysical properties in the limited range (Adun *et al.*, 2021b).

Concentration is another key factor in obtaining nanofluids, generally low concentrations of nanoparticles, less than 0.5% are useful to avoid the agglomeration of these.

A. Stability

Although nanomaterials are considered materials with dimensions on the scale of 1 to 100 nm, within this range, different sizes of nanoparticles can be obtained by different synthesis processes. The shape, type and size of nanoparticles are key factors in the stability of nanofluids and have a direct impact on the period of stability, as well as on the type and nature of the base liquid used (Al-Waeli *et al*., 2019a).

The challenge in the preparation of nanofluids is to obtain a stable suspension avoiding the agglomeration of the nanoparticles, since the thermal conductivity depends on the dispersion stability of the added nanoparticles and they must remain in suspension for a considerable period of time. However due to their large surface area and the instability of nanoparticles due to the unsaturation of the outermost atoms and therefore a high surface energy (Sezer *et al*., 2019) these have a high tendency to cluster due to van der Waals interactions (Eltaweel and Abdel-Rehim, 2019), especially when these dominate the repulsion forces, the aggregation of the nanoparticles can cause subsequent sedimentation and generate problems during the operation of the equipment in which these nanofluids are used.

Metal nanoparticles can rapidly cluster or congeal due to their high surface energy and high activity (Li *et al*., 2019).

The key variable to achieve a stable nanofluid is to avoid agglomeration, which can be achieved by physical or chemical treatment. In physical treatment, dispersion can be achieved mechanically through the use of ultrasound (Mashali *et al*., 2019) however, it has been shown that the use of ultrasonic vibration to form a nanoparticle suspension can produce a suspension that is not completely stable (Al-Waeli *et al*., 2019a). Another way to achieve dispersion is to vary or generate surface charge on the nanoparticles in such a way that repulsion occurs by load avoiding agglomeration.

Chemical dispersion is carried out by adding surfactants or polymers (Ho *et al*., 2019; Mashali *et al*., 2019) or by varying the pH of the medium.

The addition of surfactants (Table 1) improves the stability, thermal conductivity and heat transfer of the nanoparticle (Ho *et al*., 2019).

Surfactants are generally compound that reduce the surface tension between two liquids or a liquid and a solid. Surfactants are usually organic compounds. The stability of a nanofluid depends on the surfactant used to decrease the deposition of nanoparticles in the emulsion suspension. The deposition process significantly reduces

Table 1. Surfactants used to stabilize nanoparticles in suspension.

Name	Ref.
arabic gum	(Sun *et al*., 2019)
potassium oleate	(Parametthanuwat *et al*., 2015)
dodecyl betaine (DB)	(Kim *et al*., 2018)
sodium dodecyl sulfate (SDS)	(Al-Waeli *et al*., 2019a; Chakraborty *et al*., 2019; Kim *et al*., 2018)
sodium dodecyl benzene sulfonate (SDBS)	(Al-Waeli *et al*., 2019a; Kim *et al*., 2018)
sodium salicylate	(Sun *et al*., 2019)
sodium deoxycholate	(Al-Waeli *et al*., 2019a)
cetyl-trichromyl ammonium bromide	(Al-Waeli *et al*., 2019a)
cetyl trimethyl ammonium bromide (CTAB)	(Al-Waeli *et al*., 2019a)
cetyl trimethyl ammonium chloride	(Sun *et al*., 2019)
dodecyl trimethyl ammonium bromide (DTAB)	(Al-Waeli *et al*., 2019a)
polyvinyl pyrrolidone (PVP)	(El-Salamony and Morsi, 2018)
ammonium cetyl cetyl (CTAB)	(Al-Waeli *et al*., 2019a)
sodium deoxycholate	(Al-Waeli *et al*., 2019a)
triton X-100	(Gao *et al*., 2019)
tween 20	(Chakraborty *et al*., 2019; Sezer *et al*., 2019)
tween 80	(Sezer *et al*., 2019)
1,2-bis (cetyldimethylammonium) ethane dibromide (16–2–16), 1,3-bis (cetyldimethylammonium) propane dibromide (16–3–16), 1,4-bis (cetyldimethylammonium) butane dibromide, (16–4–16), 1,6-bis (cetyldimethylammonium) hexane dibromide (16–6–16), and 1,8-bis(cetyldimethylammonium) octane dibromide (16–8–16)	(Gao *et al*., 2019)

thermal conductivity of nanofluids and therefore reduces heat transfer (Al-Waeli et al., 2019).

While the trend is that the addition of surfactants to nanofluids leads to an improvement in nanofluid stability, in thermal conductivity and heat transfer performance, the presence of surfactants may also decrease thermal conductivity (Al-Waeli *et al*., 2019a; Chakraborty *et al*., 2019), especially when its concentration is increased due to the fact that a thin layer is formed on the nanoparticles which hinders the heat transfer of the nanofluid (Chakraborty *et al*., 2019).

On the other hand, the use of surfactants is restricted to low temperature applications because at high temperatures, bubbles can form that significantly affect the heat transfer efficiency (Eltaweel and Abdel-Rehim, 2019).

B. Surface tension

Surface tension could be defined as the property of the surface of a fluid which allows it to withstand an external force, due to the cohesive nature of the fluid particles (Traciak and Zyła, 2022).

Surface tension is one of the main properties that influences the heat transfer performance of a thermal system. Surface tension is defined as the force acting on the liquid surface by the length of the surface perpendicular to the force (Ramesh and Prabhu, 2011). Surface tension has a significant impact on the boiling process, since bubble deflection and interfacial equilibrium depend on it (Ciloglu and Bolukbasi, 2015; Fang *et al*., 2015).

Single-particle nanofluids

Authors like Vafaei *et al*. (Vafaei and Wen, 2011) point out that the addition of nanoparticles can play a dual role. This way, the suspended particles modify the dynamics of the bubbles significantly by varying the contact angles, the volume of the bubble output and the frequency, while the nanoparticles deposited on the heating surface modify the wettability of the surface and reduce the thermal resistance of the evaporator and condenser. The techniques used for ST and W measurement of nanofluids are similar to those developed and exploited for common liquids. Surface tension results are influenced by many factors, such as: measurement methods, measurement instruments, nanoparticle sizes, base fluids, and concentrations. Because of this, there are conflicting conclusions regarding changes in surface tension as a result of the addition of nanoparticles.

C. Viscosity

Viscosity is the resistance of liquids to deformation caused by shear or longitudinal stresses (Yang *et al*., 2020), governs the ease of flow.

The viscosity of nanofluids is also crucial for thermal and energy applications. In fact, the pumping power in energy and heat systems is related to the viscosity of nanofluids, and the pressure drop in flow systems is directly related to viscosity.

Single nanofluids

Nanofluids exhibit significantly higher viscosity compared to their base fluids and increase further with increasing nanoparticle concentration. Through a thermal and hydraulic analysis, Prasher *et al*. (2006) demonstrated that the relative increase in viscosity must be approximately four times greater than the relative increase in thermal conductivity for nanofluids to be better than base liquid in heat transfer applications under a laminar regime. This means that if the thermal conductivity of a given nanofluid increases by 25% at a certain concentration of nanoparticles, the increase in viscosity of that nanofluid at that concentration must be within 100% for its heat transfer performance to be superior to the base fluid alone. While nanofluids exhibit higher viscosities compared to their base fluids, other significantly improved thermal properties and characteristics such as thermal conductivity, heat transfer coefficient, and critical boiling heat flux can fully offset that drawback, making this class of fluids a strong candidate in the new generation of refrigerants (Suganthi and Rajan, 2017).

With laminar flow, the benefit of using nanofluids is evaluated from the viscosity ratio and improvement of thermal conductivity, denoted C_μ and C_k respectively, and is achieved when the following criteria are met (Timofeeva *et al*., 2011):

$$\frac{C_\mu}{C_k} < 4 \tag{1}$$

However, this implies that both the viscosity and the thermal conductivity ratio of nanofluids increase linearly with respect to the volume fraction of the nanoparticles, whatever the temperature tested, in the following ways:

$$\frac{\mu_{nf}}{\mu_{bf}} \approx 1 + C_\mu \Phi \tag{2}$$

$$\frac{k_{nf}}{k_{bf}} \approx 1 + C_k \Phi \tag{3}$$

where, μ_{nf} is the viscosity of the nanofluid, μ_{bf} is the viscosity of the base fluid, k_{nf}, k_{bf} the thermal conductivity of the nanofluid and the base fluid respectively and Φ corresponds to the volume fraction of nanoparticles. Under a turbulent regime, the heat transfer rate and the efficiency of nanofluids depend on the totality of the thermophysical properties of the fluid, and can be evaluated considering the Mouromtseff number (Mo), defined as follows (Timofeeva *et al*., 2011):

$$M_o = \frac{\rho^a k^b {C_p}^c}{\mu^d} \tag{4}$$

where, ρ, C_p, μ corresponds to the density, the specific heat and the viscosity respectively. The exponents a, b, c and d take appropriate values for the heat transfer and the corresponding heat transfer correlation. For a specific nanofluid, these thermophysical properties depend on the nanoparticle material, the base fluid, and the volumetric concentration of the nanoparticle.

Therefore, a nanofluid is considered to be efficient when the Mouromtseff number ratio of nanofluid and base fluid is greater than 1. The higher this ratio, the greater the potential of the nanofluid as a cooling fluid.

Regarding the influence of the shape of the nanoparticles on the viscosity, the flow resistance of the fluids in the presence of non-spherical particles is more pronounced than those in the presence of spherical particles (Bhattacharya and Sharma, 2016).

Hybrid nanofluids

The viscosity of hybrid nanofluid depends on the synthesis and preparation methods, nanoparticles size and shape, volume fraction, concentration, and temperature. The kinematic viscosity is inversely proportional to the temperature of the hybrid nanofluid (Muneeshwaran *et al.*, 2021).

Chaitanya Lahari *et al.* (2022) studied Cu-SiO_2 hybrid nanofluids produced in a glycerine-water combination base liquid with concentrations of 0.2, 0.6, and 1.0 percent, they observed that viscosity of nanofluids rises with volume concentration and falls with temperature, the same correlation was observed by Huminic *et al.* (2021)

D. Thermal conductivity

Thermal conductivity is directly related to heat transfer capabilities of fluids.

Single nanofluid

In nanofluids, the high thermal conductivities of solid nanoparticles effectively increase the thermal conductivity of suspensions. Nanofluids have higher thermal-conductivity and single-phase heat transfer coefficient than base fluid (Yang *et al*., 2020).

According to Suganti and Rajan (2017) the increased thermal conductivity of nanofluids can be attributed to various mechanisms at the molecular level, such as microconvection-induced Brownian motion, interfacial fluid stratification, and particle clustering. The influence of these mechanisms at the molecular level on the thermal conductivity of nanofluids depends on several physical factors such as: the size and shape of the nanoparticles, the morphology of the aggregates, the nanoparticle-liquid interaction, the temperature, the viscosity, etc.

Maheshwary *et al*. (2020) found that there is a relationship between the shape of the nanoparticles and the thermal conductivity which is associated with the specific surface area of the nanoparticles.

Esfahani *et at*. (2016) demonstrated that there is an optimal concentration of nanoparticles at which the particle size and viscosity of graphene oxide nanofluids show a significant improvement in thermal conductivity, and further concentration increases do not have a significant effect on the improvement of thermal conductivity.

On the other hand, experimental studies on the influence of particle shape on thermal conductivity of dispersions indicate that nanofluids containing cylindrical/ elongated / rod-shaped particles have a higher thermal conductivity compared to nanofluid that contain spherical particles (Murshed and Estellé, 2017). The decrease in particle size resulted in an increase in the specific surface area; hence the more interaction between particles and between molecules of base fluids and nanoparticles (Żyła *et al*., 2018).

There are some particularities for some materials, for example the carbon nanotube nanofluids enhanced their thermal conductivities however fullerene nanofluid decreased its thermal conductivity which arose from difference in their molecular structures (Ueki *et al*., 2017).

Hybrid nanofluid

Thermal conductivity of the hybrid nanofluids is a strong function of the type of nanoparticles and their concentration, type of base fluid, and the operating temperature (Muneeshwaran *et al.*, 2021)

The increase in thermal conductivity of hybrid nanofluids depends on many parameters like: accumulation of particles, the volume fraction of nano-particles, brownian motion, thermophoresis, size of nano-particles, shape of nano-particles, The thickness of the fluid layer between the nano-particles and temperature (Yang *et al*., 2020).

For instance Vărdaru *et al*., (2022) studied the graphene oxide (GO)-silicon (Si)/water hybrid nanofluid and found that the thermal conductivity increases both with rising temperature and with increasing graphene oxide content. Similarly (Chaitanya Lahari *et al*., 2022) observed that thermal conductivity rose as volume concentration and temperature increased.

E. Heat transfer

Hybrid nanofluid

Hanafi *et al*. (2022) studied pure water as the base fluid, Al_2O_3-Cu/water hybrid nanofluid, and two types of single-particle nanofluids which are alumina, and copper nanofluids. In comparison with water as the base fluid, there is an increase in the average heat transfer coefficient of the target surface of about 8.73% for hybrid nanofluid, 1.89% for Al2O3 nanofluid, and 0.17% Cu nanofluid. Hybrid nanofluid shows the highest heat transfer performance and reduces the greatest amount of heat from the surface to the fluid.

E. Density

Thermal conductivity and viscosity are not sufficient to theoretically calculate the heat transfer coefficient. It is also necessary to know the density and specific heat. These properties must be accurately determined as they have a considerable effect on nanofluid flux and heat transfer characteristics. The most important influence of the density is in the design of a piping system where together with the viscosity it influences the pressure drop and the pumping power. Furthermore, this property is related to the stability of the suspended system.

Some researchers have treated the density of nanofluids using various mixing rules. For example, Sun and Teja (2003) found that density and viscosity could be correlated using mixing rules based on mass fraction. In 1988 Pak and Cho (Bock Choon Pak, 2013) adopted the following equation for nano-sized particles:

$$\rho_{nf} = \rho_P \varphi + \rho_{bf}(1-\varphi) \tag{5}$$

where: ρ_{nf} is the density of the nanofluid, ρ_P is the density of the particle, ρ_{bf} is the density of the base fluid, φ is the concentration of the volume of the particle and ρ_{bf} is the density of the base fluid. This correlation has been based on the ideal gas mixing theory (mixing model), and models the density of nanofluids for a volume fraction equal to or less than 1% (Sharifpur *et a*l., 2016). Vajjha *et at.* (2009) demonstrated that the density values of the Al_2O_3 and Sb_2O_5: SnO_2 nanofluids show agreement with Eq. 5. That is, as the volume concentration of the nanofluids increases, the density value also increases. This increase is compatible with the addition of higher density particles to the base fluid. Other recent research (Sharifpur *et al*., 2016) shows that the usual approach (mixing model) for the density of nanofluids offers an overestimate, and the gap increases with increasing volume fraction. This gap shows that the nanolayer must be considered for density predictions. On the other hand, when evaluating the density-temperature relationship, the experimental data (Montazer *et al*., 2018; Żyła *et al*., 2018) demonstrate that the density decreases significantly with increasing temperatures.

F. Specific heat capacity

Syngle nanofluid

Noraldeen *et al*. (2022) studied, the particle size, interface, and temperature effects on the specific heat capacity of Cu-water nanofluid, The results showed that the specific heat capacity increases with increasing nanoparticles size, but increases with decreasing temperature.

Jamei *et al*. (2021) found that the specific heat capacity decreasing with increases volume fraction.

Hybrid nanofluids

Specific heat capacity of hybrid nanofluids, a key thermal property in energy systems is affected by the size of the nanoparticles, nanoparticle volume concentration and temperature. Nanoparticle volume concentration have an inverse relationship with the specific heat capacity, an increase in temperature improves the specific heat capacity, and this is more significant at temperatures above 50℃ (Adun *et al*., 2021b).

Adun *et al*. (2021a) studied the specific heat capacity of Fe_3O_4-Al_2O_3-ZnO water-based nanofluid, in three mixture ratios: 1:1:1, 1:2:1 and 1:1:2, the result showed that there exists a linear effect of temperature on the specific heat capacity of the ternary hybrid nanofluid. Also, when the volume concentration increases the specific heat capacity to decrease.

IX. NANOFLUIDS APPLICATIONS

Nanofluids have been shown to have great potential to improve heat transfer and are well suited for application in different heat exchangers. According to most experimental and theoretical studies, nanoparticle suspensions significantly improve heat transfer, and the heat transfer coefficient of nanofluids is found to be greater than that of their base fluid, both under heat transfer by natural as well as forced convection. This will offer an opportunity for engineers to develop highly compact and effective heat transfer equipment for many industrial applications, including transportation, nuclear reactors, electronic component cooling, and biomedical.

A. Automotive applications

The energy crisis and fuel economy have created competition between car manufacturers. Designers must improve the aerodynamic designs of vehicles to reduce the amount of energy required and overcome drag force. Unfortunately, they face the fact that more than 50% of the vehicle's total energy production is lost by overcoming aerodynamic drag. Therefore, it is required to replace the poor cooling medium, like ethylene glycol-water mixture, with nanofluids to remove heat of a relatively smaller size (Bigdeli *et al*., 2016; Devendiran and Amirtham, 2016).

Paul *et al.* (2019) evaluated a graphene-based nanolubricant functionalized with dodecylamine in a commercially available lubricant (motor oil), noting that the nanolubricants reduce the coefficient of friction by approximately 40% compared to the base motor oil, which is due to the formation of a tribofilm.

Sivalingam *et al*. (2022) evaluated the optimization of automobile radiators with MWCNT dispersed in glycol determined the improvement of heat transfer by forced convection by the dispersed MWCNT.

Another focus of nanofluids is to increase the efficiency of engine oil. Siddique *et al*. (2022) estudied nanofluid containing molybdenum disulfide (MoS_2) nanoparticles. It was found that the nanoparticles of MoS_2 enhance the lubrication and heat transport rates of engine oil.

B. Biomedical applications

In recent years, nanofluids have contributed to a wide range of applications in medical applications and in the biomedical industry.

Applying magnetic nanofluid systems is an important route for targeted drug delivery, hyperthermia, and differential diagnosis (Sheikhpour *et al*., 2020)

It has been found that iron-based nanoparticles can be used as drug delivery vehicles and have therefore been used in nanopharmaceutical applications (Godson *et al*., 2010). They can also be used to kill cancer cells without affecting nearby healthy cells by producing higher temperatures around tumors (Godson *et al*., 2010). On the other hand, nanofluids can also be used in cryosurgery, which is a procedure that uses freezing to destroy unwanted tissues (Tzeng *et al*., 2005).

C. Applications as refrigerants

A major amount of domestic energy consumption is spent on refrigeration and space cooling appliances (Bharathwaj Praveen *et al*., 2021). Many researchers have experimented with the use of nanofluids as an engine coolant. Improvements have been reported in the thermal properties of nanofluids compared to conventional refrigerants.

TiO_2 nanolubricant was used to study the performance of domestic air conditioner, the original system has R22 refrigerant. Three alternate refrigerant blends was used, results showed that the selected blends with nanolubricant have higher coefficient of performance compared to R22 (Ahmed and Ahamed, 2022).

Liu *et al*. (2018) prepared a new type of nanofluid phase change materials by suspending small amounts of TiO_2 nanoparticles in a saturated aqueous solution of $BaCl_2$. The cold storage/supply rate and cold storage/supply capacity increased much more than that of the aqueous $BaCl_2$ solution without added nanoparticles. The higher thermal efficiencies of nanofluid indicate that they have a potential to replace conventional fluids in cold storage applications.

D. Solar energy conversion systems

Diverse range of solar energy conversion systems has been employed to convert solar energy into desired useful form e.g. photothermal conversion, photoelectric conversion, photochemical conversion, and photothermal-photoelectric conversion (Shah and Ali, 2019).

The photovoltaic panel's efficiency will drop when the surface temperature rises, that will also have an adverse effect on the panel's performance and lifespan. Therefore, the cooling of the photovoltaic panel will increase the electrical efficiency (Murtadha and Adil, 2022).

Thermal energy storage as in solar thermal systems in the form of latent and sensitive heat has become an important aspect of energy management, with an emphasis on the efficient use and conservation of waste heat and solar energy in the industry and in buildings.

Murtadha *et al*. (2022) compare the three concentrations of Titanium Oxide nanofluid (1 wt%,2 wt%,3 wt%), Cooling by nanofluid at concentration (3 wt%) had the highest efficiency (19.23%).

F. Other applications

Philip and Shina (2012) developed a ferrofluid-based emulsion to select different wavelength bands in the UV, visible and IR regions. The desired range of wavelengths, bandwidth, and percent reflectivity could be easily controlled through the use of suitably adapted ferrofluid emulsions.

Aqueous dispersion of silica nanoparticles can improve oil recovery through wettability alteration via rock/fluid and fluid/fluid interactions, adhesion force between these non-polar moieties and minerals decrease with increasing nanofluid concentration (Afekare *et al*., 2020).

Rahman *et al*. (2019) reported on the performance of nanofluids cooling and lubrication in turning operation of the superalloys, in particular, titanium alloys, they found that the increase in nanoparticle concentration led to the decrease of nanolubrication effectiveness, and that The use of canola nanofluid containing 0.5 vol.% Al_2O_3 inhibió los defectos de la superficie e impartió una textura superficial muy suave.

X. CONCLUSIONS

This review shows the wide spectrum of nanomaterials used to obtain nanofluids and the importance of the variables used for their evaluation, as well as the use-fulness and advantage of nanofluids in various applications, from the simplest to the most complex.

The development of the nanofluids faces challenges as the lack of agreement between experimental results from different groups, the poor performance of suspensions; and lack of theoretical understanding of the mechanisms.

In some cases, the properties of simple nanofluids and hybrid nanofluids have similar behaviors or depend on the same variables, although in other cases they present different behaviors, as well as different behavior in response to the same variable. In some cases, the behavior depends of the particular type of nanomaterial.

The challenge of nanofluid development lies in understanding how micro- and nanoscale interactions between particles and fluids affect the thermophysical properties of the suspension to identify new and unique applications for different fields.

REFERENCES

Abbas, F., Ali, H.M., Shah, T.R., Babar, H., Janjua, M.M., Sajjad, U. and Amer, M. (2020) Nanofluid: Potential evaluation in automotive radiator. *J. Mol. Liq.* **297**, 112014.

Abbasi, A., Gul, M., Farooq, W., Ullah, S., Aydi, A., Ayadi, B., Eladeb, A. and Kolsi, L. (2022) A comparative thermal investigation for modified hybrid nanofluid model (Al2O3–SiO2–TiO2)/(C2H6O2) due to curved radiated surface. *Case Stud. Therm. Eng.* **37**, 102295.

Abhilash, P., Raghupati, U. and Nanda Kumar, R. (2021) Design and CFD analysis of hair pin heat exchanger using aluminium and titanium carbide nanofluids. *Mater. Today Proc.* **39**, 764–770.

Adun, H., Kavaz, D., Wole-Osho, I. and Dagbasi, M. (2021a) Synthesis of Fe3O4-Al2O3-ZnO/water ternary hybrid nanofluid: Investigating the effects of temperature, volume concentration and mixture ratio on Specific heat capacity, and development of Hybrid machine learning for prediction. *J. Energy Storage.* **41**, 102947.

Adun, H., Wole-Osho, I., Okonkwo, E.C., Kavaz, D. and Dagbasi, M. (2021b) A critical review of specific heat capacity of hybrid nanofluids for thermal energy applications. *J. Mol. Liq.* **340**, 116890.

Afekare, D., Gupta, I. and Rao, D. (2020) Nanoscale investigation of silicon dioxide nanofluids and implications for enhanced oil recovery – An atomic force microscope study. *J. Pet. Sci. Eng.* **191**, 107165.

Ahmed, M.I. and Ahamed, J.U. (2022) TiO2 nanolubricant: An approach for performance improvement in a domestic air conditioner. *Results Mater.* **13**, 100255.

Al-Waeli, Ali H.A., Chaichan, M.T., Kazem, H.A. and Sopian, K. (2019a) Evaluation and analysis of nanofluid and surfactant impact on photovoltaic-thermal systems. *Case Stud. Therm. Eng.* **13**, 100392.

Al-Waeli, Ali H.A., Chaichan, M.T., Sopian, K. and Kazem, H.A. (2019b) Influence of the base fluid on the thermo-physical properties of PV/T nano fluids with surfactant. *Case Stud. Therm. Eng.* **13**, 1–8.

Ali, A.R.I. and Salam, B. (2020) A review on nanofluid: preparation, stability, thermophysical properties, heat transfer characteristics and application. *SN Appl. Sci.* **2**, 1636.

Azmi, W.H., Sharif, M.Z., Yusof, T.M., Mamat, R. and Redhwan, A.A.M. (2017) Potential of nanorefrigerant and nanolubricant on energy saving in refrigeration system – A review. *Renew. Sustain. Energy Rev.* **69**, 415–428.

Babar, H. and Ali, H.M. (2019) Towards hybrid nanofluids: Preparation, thermophysical property-es, applications, and challenges. *J. Mol. Liq.* **281**, 598–633.

Bashirnezhad, K., Bazri, S., Safaei, M.R., Goodarzi, M., Dahari, M., Mahian, O., Dalkiliça, A.S. and Wongwises, S. (2016) Viscosity of nanofluids: A review of recent experimental studies. *Int. Commun. Heat Mass Transf.* **73**, 114–123.

Bharathwaj Praveen, R., Shaik, J., Raju, J.J., Padmanathan, P. and Satheesh, A. (2021) A critical review on nanorefrigerants: Boiling, condensation and tribological properties. *Int. J. Refrig.* **128**, 139–152.

Bhattacharya, A. and Sharma, S. (2016) Drinking water contamination and treatment techniques. *Appl. Water Sci.* **7**, 1043–1067.

Bigdeli, M.B., Fasano, M., Cardellini, A., Chiavazzo, E. and Asinari, P. (2016) A review on the heat and mass transfer phenomena in nanofluid coolants with special focus on automotive applications. *Renew. Sustain. Energy Rev.* **60**, 1615–1633.

Bock Choon Pak, Y.I.C. (2013) Hydrodynamic and Heat Transfer Study of Dispersed Fluids With Submicron Metallic Oxide. *Exp. Heat Transf. A J. , Therm. Energy Transp., Storage, Convers.* 37–41.

Chaitanya Lahari, M.L.R., Sesha Talpa Sai, P.H.V, Sharma, K.V. and Narayanaswamy, K.S. (2022) Thermal conductivity and viscosity of glycerine-water based Cu-SiO2 hybrid nanofluids. *Mater. Today Proc.* **66,** 1823-1829.

Chakraborty, S. and Panigrahi, P.K. (2020) Stability of nanofluid: A review. *Appl. Therm. Eng.* **174**, 115259.

Chakraborty, S., Sengupta, I., Sarkar, I., Pal, S.K. and Chakraborty, S. (2019) Effect of surfactant on thermo-physical properties and spray cooling heat transfer performance of Cu-Zn-Al LDH nanofluid. *Appl. Clay Sci.* **168**, 43–55.

Che Sidik, N.A., Mahmud Jamil, M., Aziz Japar, W.M.A. and Muhammad Adamu, I. (2017a) A review on preparation methods, stability and applications of hybrid nanofluids. *Renew. Sustain. Energy Rev.* **80**, 1112–1122.

Che Sidik, N.A., Witri Mohd Yazid, M.N.A. and Mamat, R. (2017b) Recent advancement of nanofluids in engine cooling system. *Renew. Sustain. Energy Rev.* **75**, 137–144.

Ciloglu, D. and Bolukbasi, A. (2015) A comprehensive review on pool boiling of nanofluids. *Appl. Therm. Eng.* **84**, 45–63.

Cimbala, R., Havran, P., Király, J., Rajňák, M., Kurimský, J., Šárpataky, M., Dolník, B. and Paulovičová, K. (2022) Dielectric response of a hybrid nanofluid containing fullerene C60 and iron oxide nanoparticles. *J. Mol. Liq.* **359**, 119338.

Devendiran, D.K. and Amirtham, V.A. (2016) A review on preparation, characterization, properties and applications of nanofluids. *Renew. Sustain. Energy Rev.* **60**, 21–40.

Dhinesh Kumar, D. and Valan Arasu, A. (2018) A comprehensive review of preparation, characteri-zation, properties and stability of hybrid nanofluids. *Renew. Sustain. Energy Rev.* **81**, 1669–1689.

El-Salamony, R.A. and Morsi, R.E. (2018) Stable gallium oxide@ silica/polyvinyl pyrrolidone hybrid nanofluids: Preparation, characterization, and photo-activity toward removal of malachite green dye. *J. Mol. Liq.* **271**, 589–598.

Eltaweel, M. and Abdel-Rehim, A.A. (2019) Energy and exergy analysis of a thermosiphon and forced-circulation flat-plate solar collector using MWCNT/ Water nanofluid. *Case Stud. Therm. Eng.* **14**, 100416.

Esfahani, M.R., Languri, E.M. and Nunna, M.R. (2016) Effect of particle size and viscosity on thermal conductivity enhancement of graphene oxide nanofluid. *Int. Commun. Heat Mass Transf.* **76**, 308–315.

Fang, X., Wang, R., Chen, W., Zhang, H. and Ma, C. (2015) A review of flow boiling heat transfer of nanofluids. *Appl. Therm. Eng.* **91**, 1003–1017.

Ganvir, R.B., Walke, P.V. and Kriplani, V.M. (2017) Heat transfer characteristics in nanofluid—A review. *Renew. Sustain. Energy Rev.* **75**, 451–460.

Gao, T., Li, C., Zhang, Y., Yang, M., Jia, D., Jin, T. and Hou, Y. (2019) Dispersing mechanism and tribological performance of vegetable oil-based CNT nanofluids with different surfactants. *Tribiology Int.* **131**, 51–63.

Godson, L., Raja, B., Mohan Lal, D. and Wongwises, S. (2010) Enhancement of heat transfer using nanofluids- An overview. *Renew. Sustain. Energy Rev.* **14**, 629–641.

Goharkhah, M., Ashjaee, M. and Shahabadi, M. (2016) Experimental investigation on convective heat transfer and hydrodynamic characteristics of magnetite nanofluid under the influence of an alternating magnetic field. *Int. J. Therm. Sci.* **99**, 113–124.

Goud, J.S., Srilatha, P., Varun Kumar, R.S., Kumar, K.T., Khan, U., Raizah, Z., Gill, H.S. and Galal, A.M. (2022) Role of ternary hybrid nanofluid in the thermal distribution of a dovetail fin with the internal generation of heat. *Case Stud. Therm. Eng.* **35**, 102113.

Hanafi, N.S.M., Ghopa, W.A.W., Zulkifli, R., Abdullah, S., Harun, Z., Radzi, M. and Mansor, A. (2022) Numerical simulation on the effectiveness of hybrid nanofluid in jet impingement cooling application. *Energy Reports.* **8**, 764–775.

Ho, C.J., Liao, J.C., Li, C.H., Yan, W.M. and Amani, M.

(2019) Experimental study of cooling characteristics of water-based alumina nanofluid in a minichannel heat sink. *Case Stud. Therm. Eng.* **14**, 1–9.

Huminic, G. and Huminic, A. (2018) Hybrid nanofluids for heat transfer applications – A state-of-the-art review. *Int. J. Heat Mass Transf.* **125**, 82–103.

Huminic, G., Huminic, A., Fleacă, C., Dumitrache, F. and Morjan, I. (2021) Experimental study on viscosity of water based Fe–Si hybrid nanofluids. *J. Mol. Liq.* **321**, 114938.

Jamei, M., Ahmadianfar, I., Olumegbon, I.A., Asadi, A., Karbasi, M., Said, Z., Sharifpur, M. and Meyer, J.P. (2021) On the specific heat capacity estimation of metal oxide-based nanofluid for energy perspective – A comprehensive assessment of data analysis techniques. *Int. Commun. Heat Mass Transf.* **123**, 105217.

Kanti, P., Sharma, K.V, Khedkar, R.S. and Rehman, T. (2022) Synthesis, characterization, stability, and thermal properties of graphene oxide based hybrid nanofluids for thermal applications: Experimental approach. *Diam. Relat. Mater.* **128**, 109265.

Kasaeian, A., Hosseini, S.M., Sheikhpour, M., Mahian, O., Yan, W.M. and Wongwises, S. (2018) Applications of eco-friendly refrigerants and nanorefrigerants: A review. *Renew. Sustain. Energy Rev.* **96**, 91–99.

Khan, M.S., Abid, M., Ali, H.M., Amber, K.P., Bashir, M.A. and Javed, S. (2019) Comparative performance assessment of solar dish assisted s-CO2 Brayton cycle using nanofluids. *Appl. Therm. Eng.* **148**, 295–306.

Kim, S., Tserengombo, B., Choi, S., Noh, J. and Huh, S. (2018) Experimental investigation of dispersion characteristics and thermal conductivity of various surfactants on carbon based nanomaterial. *Int. Commun. Heat Mass Transf.* **91**, 95–102.

Kimpton, H., Zhang and X., Stulz, E. (2021) The temperature stability and development of a broadband silver nanofluid for solar thermal applications. *Energy Reports.* **7**, 87–96.

Kumar, M., Sawhney, N., Sharma, A.K. and Sharma, M. (2018) Thermo-physical profile of zinc oxide nanoparticles dispersed in aqueous solution of propylene glycol. *J. Mol. Liq.* **249**, 650–658.

Kumar, P. and Sarviya, R.M. (2021) Recent developments in preparation of nanofluid for heat transfer enhancement in heat exchangers: A review. *Mater. Today Proc.* **44**, 2356–2361.

Leong, K.Y., Ku Ahmad, K.Z., Ong, H.C., Ghazali, M.J. and Baharum, A. (2017) Synthesis and thermal conductivity characteristic of hybrid nanofluids – A review. *Renew. Sustain. Energy Rev.* **75**, 868–878.

Li, D., Fang, W., Feng, Y., Geng, Q. and Song, M. (2019) Stability properties of water-based gold and silver nanofluids stabilized by cationic gemini surfactants. *J. Taiwan Inst. Chem. Eng.* **97**, 458–465.

Li, J., Zhang, X., Xu, B. and Yuan, M. (2021) Nanofluid research and applications: A review. *Int. Commun. Heat Mass Transf.* **127**, 105543.

Liu, Z., Yan, Y., Fu, R. and Alsaady, M. (2018) Enhancement of solar energy collection with magnetic nanofluids. *Therm. Sci. Eng. Prog.* **8**, 130–135.

Maheshwary, P.B., Handa, C.C., Nemade, K.R. and Chaudhary, S.R. (2020) Role of nanoparticle shape in enhancing the thermal conductivity of nanofluids. *Mater. Today Proc.* **28**, 873-878.

Mashali, F., Languri, E.M., Davidson, J., Kerns, D., Johnson, W., Nawaz, K. and Cunningham, G. (2019) Thermo-physical properties of diamond nanofluids: A review. *Int. J. Heat Mass Transf.* **129**, 1123–1135.

Montazer, E., Salami, E., Yarmand, H., Chowdhury, Z.Z., Dahari, M., Kazi, S.N. and Badarudin, A. (2018) Development of a new density correlation for carbon-based nanofluids using response surface methodology. *J. Therm. Anal. Calorim.* **132**, 1399–1407.

Muneeshwaran, M., Srinivasan, G., Muthukumar, P. and Wang, C.C. (2021) Role of hybrid-nanofluid in heat transfer enhancement – A review. *Int. Commun. Heat Mass Transf.* **125**, 105341.

Munyalo, J.M. and Zhang, X. (2018) Particle size effect on thermophysical properties of nanofluid and nanofluid based phase change materials: A review. *J. Mol. Liq.* **265**, 77–87.

Murshed, S.M.S. and Estellé, P. (2017) A state of the art review on viscosity of nanofluids. *Renew. Sustain. Energy Rev.* **76**, 1134–1152.

Murtadha, T.K. and Adil, A. (2022) Optimization the performance of photovoltaic panels using aluminum-oxide nanofluid as cooling fluid at different concentrations and one-pass flow system. *Results Eng.* **15**, 100541.

Murtadha, T.K., dil Hussein, A.A., Alalwany, A.A.H., Alrwashdeh, S.S. and Al-Falahat, A.M. (2022) Improving the cooling performance of photovoltaic panels by using two passes circulation of titanium dioxide nanofluid. *Case Stud. Therm. Eng.* **36**, 102191.

Noraldeen, S.F.M., Jin, L. and Zhou, L. (2022) Size, interface and temperature effects on specific heat capacities of Cu-water nanofluid and Cu nanoparticle: A molecular analysis. *Therm. Sci. Eng. Prog.* **27**, 101157.

Parametthanuwat, T., Bhuwakietkumjohn, N., Rittidech, S. and Ding, Y. (2015) Experimental investigation on thermal properties of silver nanofluids. *Int. J. Heat Fluid Flow.* **56**, 80–90.

Paul, G., Shit, S., Hirani, H., Kuila, T. and Murmu, N.C. (2019) Tribological behavior of dodecylamine functionalized graphene nanosheets dispersed engine oil nanolubricants. *Tribol. Int.* **131**, 605–619.

Philip, J. and Shima, P.D. (2012) Thermal properties of nanofluids. *Adv. Colloid Interface Sci.* **183–184**, 30–45.

Prasher, R., Song, D., Wang, J. and Phelan, P. (2006)

Measurements of nanofluid viscosity and its implications for thermal applications. *Appl. Phys. Lett.* **89**, 67–70.

Rahman, S.S., Ashraf, M.Z.I., Amin, A.N., Bashar, M.S., Ashik, M.F.K. and Kamruzzaman, M. (2019) Tuning nanofluids for improved lubrication performance in turning biomedical grade titanium alloy. *J. Clean. Prod.* **206**, 180–196.

Ramesh, G. and Prabhu, N.K. (2011) Review of thermophysical properties, wetting and heat transfer characteristics of nanofluids and their applicability in industrial quench heat treatment. *Nanoscale Res. Lett.* **6,** 334.

Ranga Babu, J.A., Kumar, K.K. and Srinivasa Rao, S. (2017) State-of-art review on hybrid nanofluids. *Renew. Sustain. Energy Rev.* **77**, 551–565.

Roy, S., Jazaa, Y. and Sundararajan, S. (2019) Investigating the micropitting and wear performance of copper oxide and tungsten carbide nanofluids under boundary lubrication. *Wear.* **428**–**429**, 55–63.

Said, Z., Abdelkareem, M.A., Rezk, H., Nassef, A.M. and Atwany, H.Z. (2020) Stability, thermophysical and electrical properties of synthesized carbon nanofiber and reduced-graphene oxide-based nanofluids and their hybrid along with fuzzy modeling approach. *Powder Technol.* **364**, 795–809.

Said, Z. and Saidur, R. (2017) Thermophysical Properties of Metal Oxides Nanofluids. *Nanofluids Heat Transfer in Engineering Problems.* Kandelousi, M.S. (edt.)

Sanukrishna, S.S. and Jose Prakash, M. (2018) Thermal and rheological characteristics of refrigerant compressor oil with alumina nanoparticles—An experimental investigation. *Powder Technol.* **339**, 119–129.

Sanukrishna, S.S., Murukan, M. and Jose, P.M. (2018) An overview of experimental studies on nanorefrigerants recent research, sevelopment and applications. *Int. J. Refrig.* **88**, 552–577.

Sarkar, S. and Kumar Ghosh, N. (2022) Theoretical study on enhancement of thermal conductivity and viscosity with volume fraction for ethylene glycol-based iron nanofluid. *Mater. Today Proc.* **66,** 3377-3380.

Sezer, N., Atieh, M.A. and Koç, M. (2019) A comprehensive review on synthesis, stability, thermophysical properties, and characterization of nanofluids. *Powder Technol.* **344**, 404–431.

Shah, T.R. and Ali, H.M. (2019) Applications of hybrid nanofluids in solar energy, practical limitations and challenges: A critical review. *Sol. Energy* **183**, 173–203.

Sharifpur, M., Yousefi, S. and Meyer, J.P. (2016) A new model for density of nanofluids including nanolayer. *Int. Commun. Heat Mass Transf.* **78**, 168–174.

Sheikhpour, M., Arabi, M., Kasaeian, A., Rabei, A.R. and Taherian, Z. (2020) Role of nanofluids in drug delivery and biomedical technology: Methods and applications. *Nanotechnol. Sci. Appl.* **13**, 47–59.

Shin, D. and Banerjee, D. (2011) Enhancement of specific heat capacity of high-temperature silica-nanofluids synthesized in alkali chloride salt eutectics for solar thermal-energy storage applications. *Int. J. Heat Mass Transf.* **54**, 1064–1070.

Siddique, I., Sadiq, K., Jaradat, M.M.M., Ali, R. and Jarad, F. (2022) Engine oil based MoS2 Casson nanofluid flow with ramped boundary conditions and thermal radiation through a channel. *Case Stud. Therm. Eng.* **35**, 102118.

Sivalingam, V., Ganesh Kumar, P., Prabakaran, R., Sun, J., Velraj, R. and Kim, S.C. (2022) An automotive radiator with multi-walled carbon-based nanofluids: A study on heat transfer optimization using MCDM techniques. *Case Stud. Therm. Eng.* **29**, 101724.

Suganthi, K.S. and Rajan, K.S. (2017) Metal oxide nanofluids: Review of formulation, thermo-physical properties, mechanisms, and heat transfer performance. *Renew. Sustain. Energy Rev.* **76**, 226–255.

Sun, B., Zhang, Y., Yang, D. and Li, H. (2019) Experimental study on heat transfer characteristics of hybrid nano fluid impinging jets. *Appl. Therm. Eng.* **151**, 556–566.

Sun, T. and Teja, A.S. (2003) Density, viscosity, and thermal conductivity of aqueous ethylene, diethylene, and triethylene glycol mixtures between 290 K and 450 K. *J. Chem. Eng. Data.* **48**, 198–202.

Sundar, L.S., Sharma, K. V., Singh, M.K. and Sousa, A.C.M. (2017) Hybrid nanofluids preparation, thermal properties, heat transfer and friction factor – A review. *Renew. Sustain. Energy Rev.* **68**, 185–198.

Sunil, J., Vignesh, J., Vettumperumal, R., Maheswaran, R. and Raja, R.A.A. (2019) The thermal properties of CaO-Nanofluids. *Vacuum* **161**, 383–388.

Tawfik, M.M. (2017) Experimental studies of nanofluid thermal conductivity enhancement and applications: A review. *Renew. Sustain. Energy Rev.* **75**, 1239–1253.

Timofeeva, E.V., Yu, W., France, D.M., Singh, D. and Routbort, J.L. (2011) Base fluid and temperature effects on the heat transfer characteristics of SiC in ethylene glycol/H2O and H2O nanofluids. *J. Appl. Phys.* **109**, 014914.

Traciak, J. and Zyła, G. (2022) Effect of nanoparticles saturation on the surface tension of nanofluids. *Journal of Molecular Liquids.* **363**, 119937.

Tzeng, S.C., Lin, C.W. and Huang, K.D. (2005) Heat transfer enhancement of nanofluids in rotary blade coupling of four-wheel-drive vehicles. *Acta Mech.* **179**, 11–23.

Ueki, Y., Aoki, T., Ueda, K. and Shibahara, M. (2017) Thermophysical properties of carbon-based material nanofluid. *Int. J. Heat Mass Transf.* **113**, 1130–1134.

Usri, N.A., Azmi, W.H., Mamat, R., Hamid, K.A. and

Najafi, G. (2015) Thermal Conductivity Enhancement of Al2O3 Nanofluid in Ethylene Glycol and Water Mixture. *Energy Procedia*. 70, 397-402.

Vafaei, S. and Wen, D. (2011) Flow boiling heat transfer of alumina nanofluids in single microchannels and the roles of nanoparticles. *J. Nanoparticle Res.* **13**, 1063–1073.

Vajjha, R.S., Das, D.K. and Mahagaonkar, B.M. (2009) Density measurement of different nanofluids and their comparison with theory. *Pet. Sci. Technol.* **27**, 612–624.

Vărdaru, A., Huminic, G., Huminic, A., Fleacă, C., Dumitrache, F. and Morjan, I. (2022) Synthesis, characterization and thermal conductivity of water based graphene oxide–silicon hybrid nanofluids: An experimental approach. *Alexandria Eng. J.* **61**, 12111–12122.

Vital, C.V.P., Farooq, S., de Araujo, R.E., Rativa, D. and Gómez-Malagón, L.A. (2021) Numerical assessment of transition metal nitrides nanofluids for improved performance of direct absorption solar collectors. *Appl. Therm. Eng.* **190**, 116799.

Xu, X., Xu, C., Liu, J., Fang, X. and Zhang, Z. (2019) A direct absorption solar collector based on a water-ethylene glycol based nanofluid with anti-freeze property and excellent dispersion stability. *Renew. Energy*. **133**, 760–769.

Yang, L., Ji, W., Mao, M., Huang, J.N. (2020) An updated review on the properties, fabrication and application of hybrid-nanofluids along with their environmental effects. *J. Clean. Prod.* **257**, 120408.

Yarmand, H., Gharehkhani, S., Shirazi, S.F.S., Amiri, A., Montazer, E., Arzani, H.K., Sadri, R., Dahari, M. and Kazi, S.N. (2016) Nanofluid based on activated hybrid of biomass carbon/graphene oxide: Synthesis, thermo-physical and electrical properties. *Int. Commun. Heat Mass Transf.* **72**, 10–15.

Zabalegui, A., Lokapur, D. and Lee, H. (2014) Nanofluid PCMs for thermal energy storage: Latent heat reduction mechanisms and a numerical study of effective thermal storage performance. *Int. J. Heat Mass Transf.* **78**, 1145–1154.

Zhou, J., Li, X., Chen, W., Cui, R. and Wu, X. (2022) Investigation on the photothermal performance of carbon quantum dots nanofluid with high-stability. *Diam. Relat. Mater.* **128**, 109233.

Żyła, G., Vallejo, J.P. and Lugo, L. (2018) Isobaric heat capacity and density of ethylene glycol based nanofluids containing various nitride nanoparticle types: An experimental study. *J. Mol. Liq.* **261**, 530–539.

Received: August 6, 2020
Sent to Subject Editor: January 12, 2021
Accepted: February 7, 2022
Recommended by Subject Editor Ardson Vianna Jr.