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A Review of Nanofluids Synthesis, Factors Influencing Their Thermophysical Properties and Applications

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Authors' contributions

This work was carried out in collaboration among all authors. All authors jointly wrote the first draft of the manuscript. All authors jointly implemented corrections from reviewers, read and approved the final manuscript.

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ABSTRACT

Heat-generating equipment (such as transformers, computer microchips, car engines, nuclear reactors, etc.) requires an efficient cooling mechanism to safeguard them from thermal degradation and to enhance their life span. The use of Nanofluids as opposed to conventional heat transfer fluids in their cooling system is to ensure that they are properly cooled. Nanofluids display superior thermal properties and they are synthesized from nanosized materials such as metals ((Copper (Cu), Silver (Ag), Nickel (Ni), and Gold (Au)), metal oxides ((Aluminum oxide (Al_2O_3), Cupric oxide (CuO), Magnesium oxide (MgO), Zinc oxide (ZnO), Silica (SiO_2), Iron (III) oxide (Fe_2O_3), and Titania (TiO_2)), metal carbide (such as Silicon carbide (SiC)), metal nitride (such as Aluminium nitride (AlN)), or Carbon materials ((Carbon nanotubes (CNTs), Multi-wall carbon nanotubes (MWCNTs), diamond, and graphite)) suspended in base fluids (such as water, ethylene glycol, engine oil, transformer oil, vegetable oil, kerosene, toluene, etc.). The current review explores methods used in the synthesis of nanofluids (One-step method, Two-step method, Solvothermal/Hydrothermal process), factors influencing their thermophysical properties (Particle volume concentration, pH, particle size, particle shape, particle material, base fluid material,

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temperature, shear rate, and surfactants) and their applications (Heat transfer applications, automotive applications, biomedical applications, electronic applications, Nano-based microbial fuel cells, and Nano-based brake fluids).

Keywords: Nanofluid synthesis; thermophysical properties; applications.

1. INTRODUCTION

Most industrial processes and equipment generate a lot of heat and therefore require an efficient cooling mechanism that cannot be achieved by the traditional (conventional) heat transfer fluids. The enhancement of these fluids with nanosized particles (Nanoparticles) is crucial in adapting them to the current cooling demands in industrial processes and engineering equipment. Nanoparticles can be dispersed in two different ways i.e. by either dispersing a single type nanoparticle (Mono nanofluids) or dispersing more than one type of nanoparticle (Hybrid nanofluids). The resultant fluid (Mono nanofluid or Hybrid nanofluid) with attractive heat transfer properties is then applied as a coolant fluid in thermal processes. There is a growing urgency among researchers to further improve on the thermal properties of mono nanofluids prompting more research on Hybrid nanofluids. The development of hybrid nanofluids is expected to overcome cooling challenges experienced in most heat transfer applications since their thermal conductivity is more advanced compared to both mono nanofluids and traditional heat transfer fluids.

2. SYNTHESIS AND PREPARATION OF NANOFLUIDS

The two main methods used in the synthesis and preparation of hybrid nanofluids are single-step method and the two-step method.

2.1 Synthesis of Nanofluids Using Two-Step Method

Hybrid nanofluid synthesis under this method goes through two stages, the first stage being industrial production of hybrid nanopowder via chemical, physical or mechanical processes such as grinding, milling, gel process, or vapor phase method. The second stage entails suspension of the prepared hybrid nanopowder into the base fluid through processes such as high-shear mixing, ultrasonic agitation, homogenizing, ball milling, and intensive magnetic force agitation. Harandi et al. [1] in their investigation on thermal conductivity of $f - MWCNTs - FO_3O_4/EG$ hybrid nanofluid, they utilized two-step method to prepare the nanofluid by using ultrasonic vibration instrument to mix dry $f - MWCNTs$ and Fe_3O_4 nanoparticles into ethylene glycol base fluid. Akilu et al. [2] employed the wet-mixing method in preparation of (TiO_2-CuO/C)-based nanocomposites and later prepared (TiO_2-CuO/C)-EG based nanofluid via a two-step method. The major challenge that has been reported in the preparation of hybrid nanofluids by the two-step method is the agglomeration of nanoparticles which can be suppressed by the addition of dispersants or surfactants. The use of surfactants in high-temperature applications still poses a challenge making the preparation of stable hybrid nanofluids using the two-step method difficult. To overcome the difficulty advanced methods like the one-step method are used in the preparation of stable nanofluids. The advantage of using the two-step method in the synthesis of nanofluids is that it is cost-effective in producing nanofluids on large scale.

2.2 Synthesis of Nanofluids Using One-Step Method

Nanofluid synthesis using one-step method overcomes the problem of agglomeration of nanoparticles encountered in the preparation of hybrid nanofluids by the two-step method. The method combines synthesis and dispersion of hybrid nanoparticles into carrier fluid into one step getting rid of processes such as drying, storage, transportation, and dispersion of nanoparticles, this minimizes agglomeration of nanoparticles leading to the formation of stable nanofluids. The methods used under this procedure are one-step physical method and one-step chemical method. Nanofluid synthesis by one-step physical method is too costly and not suitable for industrial large scale production of nanofluids. The most preferred one-step method in the synthesis of nanofluids is one-step chemical method. H. Zhu et al. [4] proposed one-step chemical reduction method for synthesizing Cu/EG nanofluid. In the experiment, copper nanoparticles were formed by reducing $CuSO_4$ to copper by the use of Sodium hypophosphite in the presence of microwave irradiation. The same method was extended to the synthesis of Nickel/Ethylene Glycol nanofluid where Nickel sulphate was reduced to Nickel by use of Sodium hypophosphite subject to microwave irradiation.

2.3 Other Novel Methods

Nanofluids can also be prepared via a Solvothermal/ Hydrothermal process. Solvothermal synthesis is described as a chemical reaction that takes place in a solvent at a temperature above the boiling point and pressure above1 bar [5]. The medium employed in Solvothermal synthesis ranges from water, alcohol to any other organic or inorganic solvent. The process is termed as Hydrothermal when water is used as a solvent. The instruments used in the Solvothermal/Hydrothermal process include a sealed reactor (autoclave), a pressure vessel, or a high-pressure bomb. The autoclave is usually metallic with Teflon or alloy linings or containing an extra beaker, or tube made of Teflon, platinum, gold, or silver to protect the autoclave body from highly corrosive solvent held at high temperature and pressure [6]. The Solvothermal/ Hydrothermal process uses crystallization to grow particles from the solvent. The two steps involved in the process are crystal nucleation and subsequent crystal growth. The desired particle size and morphology are arrived at by controlling processing variables such as temperature, pH, reactant concentration, and additives.

3. THERMOPHYSICAL PROPERTIES OF NANOFLUIDS

Hybrid nanofluids synthesized by suspending two or more different nanoparticles in the base fluid generally show superior thermophysical properties compared to mono nanofluids and other conventional heat transfer fluids. The thermophysical properties include; thermal conductivity, convective heat transfer, viscosity, density, heat capacity, thermal diffusivity, emissivity, and optical absorption. The thermophysical properties of importance in this study are thermal conductivity, viscosity, and convective heat transfer.

3.1 Thermal Conductivity

The ability of the nanofluid to conduct heat determines its suitability for use as a coolant fluid in most equipment and industrial applications such as cooling of; nuclear reactors, computer microchips, supersonic military fighter jets, military submarines, missiles, and transformers that require faster removal of heat. Studies conducted on thermal conductivity of nanofluids show that thermal conductivity depends on various factors such as particle volume concentration, particle material, particle size, particle shape, base fluid material, temperature, additives, and acidity.

3.1.1 Thermal conductivity and particle volume concentration

The volume concentration of nanoparticles is important with regard to the thermal conductivity of nanofluids. Studies conducted by various researchers show that the addition of small nanoparticle volume fractions to the normal heat transfer fluids improves their thermal conductivity. (Esfe et al. [7]; Hemmat Esfe et al. [8]) noted a considerable improvement in the thermal conductivity of the nanofluids with rising particle volume concentration. Studies by Pang et al. [9] on thermal conductivity of (SiO_2/methanol)-nanofluid done at $20℃$ reported an increase in thermal conductivity with increasing volume concentration of nanoparticles. They reported a 14.29% enhancement in thermal conductivity above that of the base fluid at 0.5% volume concentration of nanoparticles. Aberoumand et al. [10] working with Ag/oil nanofluid noted enhancement in thermal conductivity of up to 35%. Fakoor Pakdaman et al. [11] investigating thermophysical properties of MWCNTs based nanofluids in weight fractions of 0.1%, 0.2%, and 0.4% reported a maximum enhancement in thermal conductivity of 15% at $70℃$ and maximum enhancement in viscosity by 27%. Chopkar et al. [12] studying the thermal conductivity of Ag_2Al, and Al_2Cu water and ethylene glycol based nanofluids observed that the thermal conductivity of nanofluids was 2.4 times that of the base fluid at (0.2-1.5%) concentration of nanoparticles.

3.1.2 Thermal conductivity and pH value

The pH value influences the stability and thermal conductivity of nanofluids. D. Zhu et al. [13] investigating dispersion behavior and thermal conductivity characteristics of (Al_2O_3/H_2O) nanofluids observed maximum thermal conductivity of the nanofluid in the pH range of (8.0-9.0). Murshed et al. [14] working with (TiO_2/H_2O) nanofluid to determine the thermal conductivity of the nanofluid, they observed a decline in thermal conductivity of the nanofluid with rising pH values.

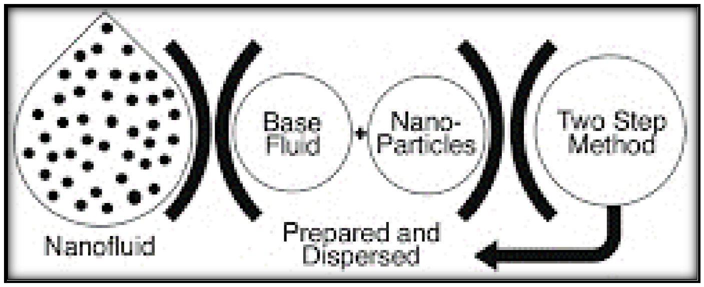

Fig. 1. Synthesis of nanofluid by two-step method
(Figure Source: Babar et al. [3])

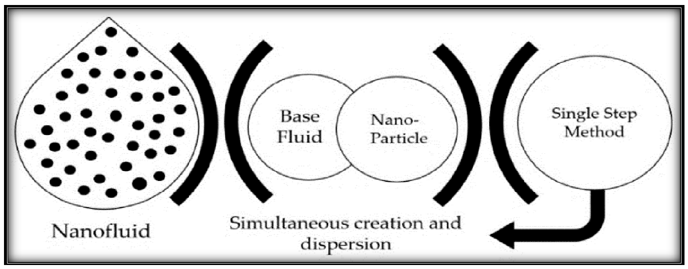

Fig. 2. Synthesis of nanofluid by one-step method
(Figure source: Babar et al. [3])

3.1.3 Thermal conductivity and particle size

The thermal conductivity of nanofluids relies on the nanoparticle diameter used in the preparation of the nanofluid. Mohammed Ali et al. [15] observed enhancement in both thermal conductivity and thermal diffusivity with increasing particle size for Al_2O_3-distilled water nanofluid. The Aluminum oxide (Al_2O_3) nanoparticles used were of the diameter (11, 25, 50, and 63nm). Beck et al. [16] experimenting with (Al_2O_3/H_2O/EG) based nanofluids with nanoparticle size ranging from (8-282 nm) reported enhancement in thermal conductivity with increasing particle size. Studies by Kim et al. [17] on thermal conductivity of (Al_2O_3, ZnO, TiO_2 /H_2O/EG) based nanofluids reported an increase in thermal conductivity with decreasing particle size, they measured thermal conductivity of the nanofluids using the transient hot-wire method. Masuda et al. [18] investigating the alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles, they reported an increase in thermal conductivity with decreasing particle size. A similar inverse relationship between particle size and thermal conductivity was also confirmed by [19] in their study on the thermal conductivity of fluids dispersed with oxide nanoparticles.

3.1.4 Thermal conductivity and particle shape

The thermal conductivity of nanofluids depends on particle morphology. A study by Xie et al. [20] on nanofluids dispersed with SiC nanoparticles reported higher thermal conductivity from nanoparticles with cylindrical shape compared to ones with spherical morphology for the same base fluid. Jeong et al. [21] experimenting with (ZnO/H_2O) nanofluid noted higher thermal conductivity of 18% above the base fluid for ZnO nanoparticles with nearly rectangular morphology and enhancement of 12% above the base fluid for nanoparticles with spherical morphology at a particle volume concentration of 5.0vol%. Murshed et al. [14] studying the thermal conductivity of TiO_2 water-based nanofluid and employing a transient hot-wire method coupled with an integrated correlation model for measurement of thermal conductivity of the nanofluid reported enhancement in thermal conductivity as a result of particle volume fraction, particle size, and particle shape. The TiO_2 nanoparticles used in the study were rod-shaped and spherical shaped.

3.1.5 Thermal conductivity and base fluid material

The base fluid (carrier fluids) in which nanomaterials are suspended during the preparation of nanofluids consist of normal heat transfer fluids such as water, ethylene glycol (EG), EG/water mixture, oils (engine oil, vegetable oil, transformer oil, kerosene oil) and polymer solutions. The thermal conductivity of a particular base fluid chosen for the preparation of nanofluid affects the overall thermal conductivity of the resultant nanofluid. Base fluids having poor thermal properties are preferred over those with good thermal transfer properties because their effective thermal conductivity upon the addition of nanoparticles is well enhanced compared to base fluids with high thermal conductivity. Usri et al. [22] investigating thermal conductivity of Al_2O_3 nanoparticles suspended in (H_2O:EG) mixture of ratios (60:40, 50:50, and 40:60) reported enhancement in thermal conductivity with rising particle concentration and temperature and a decline in thermal conductivity with rising percentage content of ethylene glycol in the mixture. Lee et al. [19] working on (Al_2O_3 and CuO/H_2O, EG) based mono nanofluids produced via a two-step method observed better thermal conductivity ratio in CuO nanoparticles than Al_2O_3 nanoparticles for the same base fluid and for the same nanoparticle the conductivity ratio of ethylene glycol-based nanofluids was higher compared to water-based nanofluids. Chopkar et al. [23] investigating thermal conductivity of Al_2Cu and Ag_2Al for water and ethylene glycol-based nanofluids observed better thermal conductivity enhancement in water-based nanofluids compared to ethylene glycol-based nanofluids.

3.1.6 Thermal conductivity and particle material

The intrinsic thermal conductivity of the suspended nanoparticle material does not give a primary effect in determining the thermal conductivity of the nanofluid. Dispersing nanoparticles of higher thermal conductivity does not guarantee higher thermal conductivity enhancement in the nanofluid. A study conducted by Hong et al. [24] showed better thermal conductivity enhancement in Fe-nanofluid compared to Cu- nanofluid yet copper conducts heat better than iron.

3.2 Viscosity

The flow properties (such as Reynolds number, convective heat transfer coefficient, and pressure drop) in any fluid depends on the viscosity of the fluid. The viscosity of Nanofluids determines their effectiveness in industrial heat transfer applications. The more viscous the nanofluid is the more the energy demand in pumping the nanofluid to keep it flowing. Nanofluid's viscosity is a function of many parameters such as Temperature, Nanoparticle volume fraction, Nanoparticle size, Nanoparticle shape, pH, Shear rate, and the properties of the base fluid.

3.2.1 Temperature and viscosity of nanofluids

The viscosity of nanofluids generally varies inversely with variations in temperature. The intermolecular forces that bind nanoparticles and base fluid together get weakened with rising temperature making the viscosity of the nanofluid to decline with rising temperature values. Shahsavar et al. [25] using (CNT-Fe_3O_4/H_2O) based hybrid nanofluid reported a decline in viscosity with rising temperatures. The study considered a temperature range of $(25℃ - 55℃)$. Hemmat Esfe et al. [8] investigating how temperature and nanoparticle concentration impacts on the rheological behavior of MWCNTs/SiO_2 (20-80)-SAE 40 hybrid nanolubricant, they noted a maximum enhancement of 30.2% in viscosity of nanolubricant at a temperature of $40℃$ and 1% volume fraction. They also reported the sensitivity of hybrid nanolubricant towards low temperatures instead of higher temperatures. Nabil et al. [26] using (TiO_2-SiO_2) hybrid nanoparticles suspended in (water: ethylene glycol) mixture and experimenting with a temperature range of $(30℃ - 80℃)$ they observed a decrease in viscosity with rising temperature. (Hemmat Esfe, Afrand, et al. [27]) working with volume fractions of (0.05, 0.075, 0.1, 0.2, 0.4, 0.5, 0.75, 1.0 vol %) and temperature ranging from $(20℃ - 50℃\ )$ they observed a maximum increase in viscosity at $40℃$ for MWCNT-ZnO/engine oil hybrid nanofluid attributing the increase to clustering of nanoparticles. They further reported a decline in viscosity in temperatures above $40℃$.

3.2.2 Nanoparticle volume fraction and viscosity of nanofluids

Studies by various researchers reveal a significant impact of nanoparticle volume fraction on the viscosity of nanofluids. Nabil et al. [26] using (TiO_2-SiO_2)/ (H_2O and EG) based hybrid nanofluid recorded an increase in dynamic viscosity by about 2% upon raising nanoparticle volume fraction from (2-3%) at a temperature of

$30°C$. Dalkılıç et al. [28] working with (SiO_2-Graphite/H_2O) based hybrid nanofluid reported a sharp rise in the viscosity of the nanofluid when silica nanoparticles were suspended in the base fluid as compared to graphite nanoparticles. A study by Afshari et al. [29] revealed a change in properties of the nanofluid beyond 0.5vol.% concentration of nanoparticles from Newtonian to pseudoplastic non-Newtonian. The study considered alumina-MWCNT/ (EG: H_2O) hybrid nanofluid. The base fluid (ethylene glycol: water) mixture was in the ratio of (20%:80%). Soltani & Akbari [30] observed Newtonian behavior in (MgO-MWCNT/EG) hybrid nanofluid. They also concluded that dynamic viscosity increased with a rising concentration of nanoparticles with 168% being the highest recorded increase at 1.0 vol. % and $60°C$. A study by Ghasemi & Karimipour [31] on the influence of temperature and mass fraction on dynamic viscosity of (CuO/paraffin) based nanofluid concluded that the impact of nanoparticle concentrations on dynamic viscosity was only significant in nanoparticle loading above 1.5wt.%.

3.2.3 Nanoparticle size and viscosity of nanofluids

The few pieces of literature available on the impact of nanoparticle size on the viscosity of nanofluids presents contradicting findings. Some papers report enhancement in viscosity with increasing particle size while others report a decrease in viscosity with increasing particle size. Namburu et al. [32] investigated viscosity and specific heat of (SiO_2/ (EG-water mixture)) based nanofluid with ethylene glycol and water mixed in the ratio (60:40). They considered (SiO_2) nanoparticles of diameter (20, 50, and 100nm). They observed Non-Newtonian behavior and a decline in viscosity with increasing particle size for the nanofluid. Chevalier et al. [33] working with (SiO_2) nanofluid of particle size (35, 94, and 190 nm) and solid volume fraction of (1.4-7%) observed Newtonian behavior and a decrease in viscosity of nanofluid with increasing particle size. A study by He et al. [34] on heat transfer and flow behavior of (TiO_2/H_2O) based nanofluid with nanoparticle diameters of (95nm, 145nm) revealed enhancement in viscosity of the nanofluid with increasing particle size and volume concentration. Pastoriza-Gallego et al. [35] investigation on the effect of particle size and polydispersity on volumetric behavior and viscosity of (CuO-water) based nanofluid resulted in a decrease in viscosity with increasing particle size.

3.2.4 Viscosity of nanofluids and base fluid material

The intrinsic properties of base fluid material used to suspend nanoparticles have a spillover effect on the overall viscosity of the resultant nanofluid. The oil-based nanofluids are preferred as nanolubricants due to their enhanced viscosity and better performance in high-temperature applications. Water-based nanofluids are easy to pump hence preferred in heat transfer applications. Sundar et al. [36] using magnetic nanodiamond-cobalt oxide (ND-CO_3O_4) nanocomposites dispersed in different base fluids (water, ethylene glycol/water mixtures) observed better enhancement in viscosity in ethylene glycol-based nanofluid compared to water-based nanofluid. They conducted their experiment using nanoparticles of weight concentration (0.05% and 0.15%) at a temperature of $(20°C \text{ and } 60°C)$. Kannaiyan et al. [37] using base fluids (H_2O, (water-EG mixture (80:20)) to form alumina/cupric oxide hybrid nanofluids in different concentrations of (0.05%, 0.1%, 0.2%) reported better thermal conductivity performance in water-based nanofluid and higher viscosity enhancement in the water-ethylene glycol-based system.

3.2.5 Viscosity of nanofluids and shear rate

The problems of rheology (deformation and flow) of materials are important in material science, engineering, geophysics, physiology, human biology, and Pharmaceutics. Fluids can be classified as Newtonian or non-Newtonian depending on the behavior of their viscosity as a function of shear rate and stress. Newtonian fluids exhibit a linear relationship between stress and strain rate while non-Newtonian fluids exhibit a non-linear relationship between stress and strain rate. Study by [38] on rheological behavior of TiO_2-MWCNT(45-55%)/10w40 hybrid nano-oil in different volume fractions of (0.05%, 0.1%, 0.25%, 0.5%, 0.75%, 1%), temperature range of $(5-55°C)$ and shear rate range of (666.65-11,999.7s^{-1}) reported non-Newtonian behavior of the nano-oil with an increasing shear rate. Bahrami et al. [39] working on hybrid nanofluids of (Fe-CuO/ (binary mixture of H_2O-EG) of proportions (20-80 vol %) observed Newtonian behavior in low concentration samples and non-Newtonian behavior in high concentration samples. Their experiment considered solid volume fractions of (0.05, 0.1, 0.25, 0.5, 1 and 1.5%), temperature range of $(25-50°C)$ and the shear rate range of (3.669-122.3s^{-1}).

Afrand et al. [40] using (Fe_3O_4-Ag/EG) hybrid nanofluid in solid volume fractions of (0.0375, 0.075, 0.15, 0.3, 0.6 and 1.2%) and varying shear rates from (12.23-122.3s^{-1}) and temperature from $(25-50℃)$ reported Newtonian behavior in samples with less than 0.3% solid volume fraction and non-Newtonian behavior in samples with solid volume fractions of (0.6% and 1.2%) which was reported to be consistent with the power-law model.

3.2.6 Particle shape and viscosity of nanofluids

Studies into the effect of particle morphology on the viscosity of nanofluids reveal varying augmentation in viscosity among various nanoparticle shapes. The investigation into the effect of particle shape on the viscosity of (alumina-EG/H_2O) nanofluid by [41] revealed better viscosity enhancement in elongated particles (platelets and cylindrically shaped nanoparticles) as compared to spherical ones at the same volume fraction. Jeong et al. [21] using ZnO nanoparticles of nearly rectangular and spherical morphology noted viscosity enhancement of 7.7% in nearly shaped rectangular nanoparticles as compared to spherical ones.

3.2.7 Effect of addition of surfactants on the viscosity of nanofluids

The use of Surfactants (dispersants) in nanofluids boosts the stability of nanofluids and suppresses clustering (agglomeration) of nanoparticles. Studies show that the use of surfactants to stabilize nanofluids affects the viscosity of the nanofluid. Murshed et al. [42] used Al_2O_3 (80nm) distilled water nanofluid and registered increased viscosity by 82% compared to 86% that was reported by [43] using Al_2O_3 (28nm) distilled water nanofluid. The two studies considered nanoparticle volume fractions of 5% and they attributed the difference in viscosity enhancement on differences in nanoparticle size, dispersion techniques, and use of surfactants. A study by Lin et al. [44] on heat transfer characteristics of Al_2O_3-nanofluid revealed enhancement in dynamic viscosity upon the addition of dispersants (surfactants) in the nanofluid. Ghadimi & Metselaar [45] inquiry into how surfactants and ultrasonic processing influences stability and viscosity of TiO_2-nanofluid and by incorporating Sodium dodecyl sulphate as a surfactant, they reported an increase in viscosity as a result of the use of surfactant in the nanofluid. Jarahnejad & Saleemi [46] using (Al_2O_3/H_2O) and (TiO_2/H_2O) nanofluids observed enhancement in viscosity upon the addition of surfactants (trioxadecane acid) in the nanofluids.

3.2.8 Effect of pH value on viscosity of nanofluids

The pH value of the nanofluid influences the Zeta potential (potential difference between base fluid and surface of nanoparticles) which in turn affects the stability and viscosity of the nanofluid. Zeta potential values of $(>+30mV\ or <-30mV)$ denotes enhanced stability of the nanofluid (absence of agglomeration of nanoparticles). Investigations by [47] revealed fluctuations in viscosity of SiO_2 nanofluid with pH values and nanoparticle size. They reported viscosity dependence on pH values in nanoparticles with diameters less than 20nm with fluctuations in viscosity being observed in the pH range of (5-7). A study by Jeong et al. [21] on viscosity and thermal conductivity of ZnO-nanofluid recorded zeta potential values of (-47.48mVand -49.15mV) indicating that the nanoparticles were stably suspended in the base fluid.

3.3 Convective Heat Transfer

The convective heat transfer coefficient of normal heat transfer fluids can be enhanced by suspending nanoparticles in them. The investigation by Madhesh et al. [48] on heat transfer characteristic of (Cu-Ti /H_2O) hybrid nanofluid for possible application as a coolant fluid reported improved convective heat transfer coefficient of up to 48.4% at 0.7% nanoparticle volume concentration. Mosayebidorcheh et al. [49] revealed a linear increase in the convective heat transfer coefficient with increasing nanoparticle volume concentration and Reynolds number. They also observed an inverse relationship between convective heat transfer coefficient, turbulent parameters, and Hartmann number. Hassan et al. [50] study into convective heat transfer and flow characteristics of (Cu-Ag/H_2O) hybrid nanofluid revealed enhanced heat transfer coefficient of the hybrid nanofluid compared to the base fluid and mono (single material) nanofluids of (Cu/H_2O and Ag/H_2O). (Chamkha & Tayebi [51]; Tayebi & Chamkha [52]) reported better enhancement in heat transfer rate in (Cu-Al_2O_3/H_2O) hybrid nanofluid compared to a single material (Al_2O_3/H_2O) nanofluid.

4. APPLICATIONS OF NANOFLUIDS

Nanofluids engineered by suspending nanosized particles (nanoparticles) in ordinary heat transfer fluids proves promising in current and future industrial and engineering processes. They are engineered to enhance the thermal properties of the normal heat transfer fluids. They are broadly used as a heat conveyor fluid in heat transfer applications, electronic applications, automotive applications, biomedical applications, used as a detergent, in microbial fuel cells among many other applications.

4.1 Heat Transfer Applications

4.1.1 Extraction of geothermal energy

The underground water gets superheated and turns into steam at very high pressure whenever it comes in contact with the hot magma. The steam generated can be harnessed to produce geothermal energy. Harnessing of this steam to generate geothermal energy requires drilling of wells deep into the earth's crust. The drilling equipment and sensors used are subjected to very high temperatures as a result of friction involved during drilling and high temperatures originating from hot magma deep within the earth's crust. Cooling of such equipment becomes important if they have to continue being used in the drilling process. Nanofluids having high thermal conductivity are deployed in cooling down pipes, machinery, and other equipment involved in the extraction of geothermal energy. Their use as a heat conveyor fluid during drilling allows sensors and other electronic devices to operate under very high temperatures allowing access to deeper and hotter regions within the earth's crust, this increases the amount of steam harnessed from the interior of the earth's crust.

4.1.2 Cooling of power distribution transformers

Transformers play a significant role in power systems by transferring electrical energy from one electrical circuit to another, or multiple circuits. They work on the principle of electromagnetic induction and they have got two sets of coils (i.e. Primary coils and secondary coils). A transformer having more primary coils and fewer secondary coils (a Step-down transformer) converts high primary voltage to a low secondary voltage. A transformer with fewer primary coils and more secondary coils (a step-up transformer) converts low primary voltage to a high secondary voltage. The to and fro energy conversion from the magnetic field to electrical energy in the transformer results in magnetic losses (Hysteresis loss and Eddy current loss) and electrical loss (i.e. copper loss). In both cases, the energy loss is dissipated in form of heat, generating heat inside the transformer. Transformers may also overheat due to factors such as (transformer overload, too much current in the neutral of the transformer, malfunction in the transformer cooling system, high harmonic content in the power supply, and sustained overvoltage). The cooling of transformers is therefore important to minimize the rate of thermal degradation. The use of oil as a coolant in the transformer can be enhanced by adding nanoparticles in it to boost its cooling ability [53-55]. A study by Farhan et al. [53] on oil-based alumina nanofluids of different wt/v ratios as a coolant fluid for heat transfer enhancement in transformers recorded an improvement in dielectric strength by 8.67% upon addition of 0.08% nanoparticles in oil. Hasan [56] using transformer oil-based nanofluids (Cu, Al_2O_3, TiO_2, and SiC) as coolants in 250KVA distribution transformer in volume fractions (1%, 3%, 5%, 7%, and 9%) reported enhancement in the dielectric of oil and increase in breakdown voltage due to the presence of nanoparticles in oil. The use of transformer oil-based nanofluids as a cooling medium was effective in lowering the temperature of the transformer compared to pure transformer oil thus safeguarding the transformer against breakdown. The SiC-oil nanofluid gave a lower transformer temperature than the rest of the nanofluids.

4.1.3 Cooling of nuclear reactors

The production of nuclear energy occurs in nuclear reactors. The various forms of nuclear reactors include light water reactors (LWR) and heavy water reactors (HWR) [57-58]. The LWR is a thermal nuclear reactor that uses ordinary water (H_2O) passing through the heart of the nuclear reactor to generate electricity. The types of LWR include ((Boiling Water Reactor (BWR), Pressurized Water Reactors (PWRs), and Supercritical Water Reactor (SWR)). The HWR is a kind of thermal nuclear reactor that uses heavy water (D_2O) produced from deuterium instead of hydrogen, plus normal oxygen. The HWR uses natural uranium. Nuclear reactors are prone to accidents that can result from natural disasters (such as earthquakes and floods), terrorism, and accidents resulting from Human errors in the operation of Reactors. The effective cooling

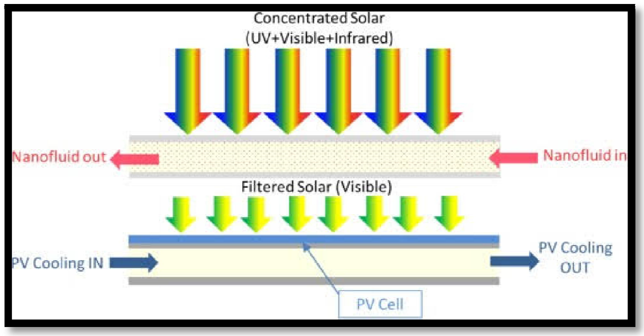

Fig. 3. Nanofluid as a working fluid in (PV/T) system
(Figure source: Goel et al. [65])

of nuclear reactors enhances safety during operation and averts major disasters during Nuclear power plant explosion. Most Nuclear power plants are water-cooled. The addition of nanoparticles in water enhances the ability of water in cooling down the reactors [59-60]. Nanofluids have been deployed as a coolant fluid in the main reactor for pressurized water reactors (PWRs), in the emergency core cooling system (ECCS) of both PWRs and BWR, and coolant for in-vessel retention of the molten core during severe accidents in high-power-density light water reactors.

4.1.4 Solar energy collection

Solar energy is regarded as one of the cleanest and most abundant forms of energy available for use by mankind. It is considered green energy and its use include heating living spaces, generation of electrical energy in solar panels, cooking in solar cookers, and heating water for use in domestic hot water systems. Solar energy harvesting requires the use of solar collectors whose operation is always limited by the working fluid used. This challenge can be overcome by incorporating fluids with high thermal conductivity as the working fluid in the solar collectors to help conduct heat very fast thereby increasing their ability to absorb solar energy. The working fluids suitable for enhancing the efficiency of these solar collectors are nanofluids [61-62]. A study conducted by X. Li et al. [63] on direct absorption solar collectors based on (SiC-MWCNTs / ethylene glycol) hybrid nanofluids reported a 97.3% improvement in solar- thermal conversion efficiency at 1 wt% hybrid nanofluid concentration. This enhanced solar-thermal conversion efficiency by the hybrid nanofluid was 48.6% higher than pure ethylene glycol. Ghodbane et al. [64] investigating the performance of linear Fresnel solar reflector based on (MWCNTs / DW) nanofluids recorded the highest thermal efficiency of 33.81% as a result of the use of nanofluid.

4.1.5 Heating living spaces in cold regions

The winter period is always characterized by very low temperatures. The heating of houses becomes necessary to survive these cold conditions. The heating elements used incorporate nanofluids as the working fluid. The use of nanofluids in the heating elements reduces the overall size of the heating elements resulting in smaller elements with the ability to deliver the same heat energy as the larger elements. Smaller elements require less amount of nanofluids, they are cheaper to buy, use less power during operation and their effect on the environment at the end of their life cycle is less because the material to be disposed of is less compared to the larger heating elements. The heating fluid commonly used is the mixture of water and ethylene or water and propylene glycol mixed in different proportions.

4.1.6 Space and defense systems

Space stations and aircrafts used in the defense industry demand for efficient lighter cooling systems due to limitations on the amount of weight that can be supported in these space stations. To achieve these ultrahigh-heat flux cooling systems, nanofluids with superior heat transfer properties are always incorporated into these cooling systems. Most military devices and equipment such as military vehicles, submarines, high-power laser diodes, jet fighters, and missiles requires high-heat flux cooling to the tune of tens of MW/m^2 for reliable operations which can only be achieved by incorporating nanofluids in their cooling systems.

4.2 Automotive Industry

Vehicular fluids such as engine oils, automatic transmission fluids, coolants, lubricants, and other synthetic high-temperature heat conveyor fluids found in radiators, engines, heating, ventilation, and air-conditioning systems are always characterized by poor thermal conductivity, incorporating nanoparticles of high thermal conductivity in these vehicular fluids improves their thermal conductivity for their suitable use in the automotive industry.

4.2.1 Nanofluid coolant in automobile radiators

The world fossil fuel reserves are dwindling as a result of the rising human population and increased demand for petroleum products from the automobile industry. The vehicle manufacturers are tasked with developing more fuel economy vehicles. The challenge faced by vehicle manufacturers is improving on the aerodynamic design of the vehicles by reducing the size of their radiators and at the same time ensuring that they are properly cooled by the smaller sized radiator. Studies conducted by Singh et al. [66] shows that incorporating nanofluid in car radiators as a coolant allows for smaller sized radiators and better positioning of the radiators which improves the aerodynamic design of the vehicles, this minimizes energy wastage resulting from the aerodynamic drag from the oncoming wind. Leong et al. [67] using copper nanoparticles in engine cooling reported a 3.8% increase in heat transfer upon the addition of 2% copper nanoparticles and a possible reduction in the frontal area by 18.7%.

4.2.2 Nanolubricants

The frictional force between moving parts of machines results in wear and tear and noise pollution resulting from the rubbing of the movable parts of the machine. The use of lubricants in machines makes them more efficient to operate and more durable. Petroleum-based hydrocarbon lubricants like oil and grease have limited use as a lubricant in modern machines and to enhance their use in modern machinery as lubricants it has been suggested that they be dispersed with nanoparticles. The use of nanoparticles in lubricants results in reduced interfacial friction and increased load-carrying capacity by the parts of the machine. Studies by Choi et al. [68] on the tribological behavior of Cu-nanoparticles dispersed in oil showed reduced friction coefficients and wear and tear that was attributed to the deposition of Cu-nanoparticles in the scars and grooves on the metal surfaces. The use of SWNTs in synthetic PAO oil by [69] for boundary lubrication showed a substantial reduction in friction and wear and tear at as low as 1wt %. Xue et al. [70] working with TiO_2 nanoparticles suspended in liquid paraffin reported enhanced load carrying capacity and reduction in wear and tear.

4.3 Biomedical Applications

Magnetic nanofluids (ferrofluids) are increasingly becoming popular in the biomedical field. Their numerous applications are attributed to their advanced thermophysical properties. The Biomedical applications of nanofluids include in Nanocryosurgery, Nano drug targeted delivery, Magnetic fluid hyperthermia for Cancer treatment, magnetic cell separation, as a contrast agent in Magnetic Resonance Imaging (MRI), and in cryopreservation.

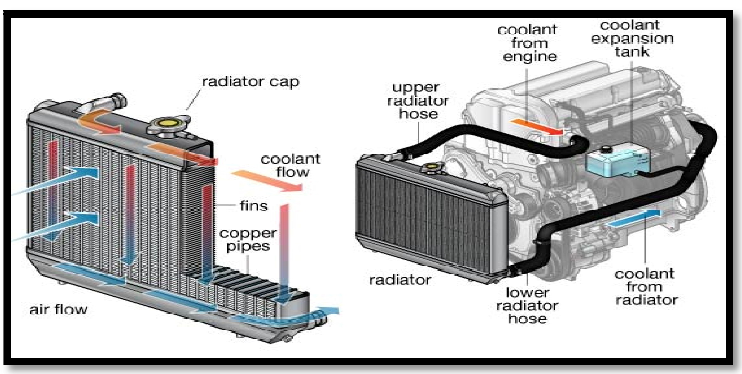

Fig. 4. The automobile radiator
(Figure source: Michael & company.com website)

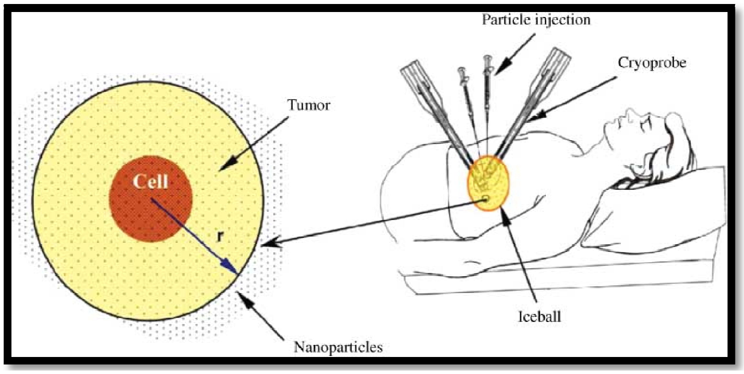

Fig. 5. Nanoparticle injection to speed up freezing of tumour cells
(Figure Source: Chen et al. [71])

4.3.1 Nanocryosurgery

Cryosurgery refers to the freezing therapy used in the controlled destruction of tumour tissues. Traditional therapies (chemotherapy and radiotherapy) used in the treatment of cancer have proved effective in the treatment and management of cancer, but they come with so many negative side effects to the neighbouring healthy cells and tissues. The development of safer methods for treatment and management of cancer is therefore a priority. Cryosurgery as a therapy for destroying tumour (cancerous) cells comes with its clinical advantages compared to the traditional therapies. To enhance the effectiveness of cryosurgery, Nanoparticles of high thermal conductivity can be incorporated in this clinical procedure hence the term Nanocryosurgery. The intentional loading of target tissues with nanoparticles of high thermal conductivity has shown the ability to speed up the freezing rate thus lowering the final tumour temperature, this enhances the volume of ice that could have been obtained in the absence of nanoparticles. Nanoparticles preferred in Nanocryosurgery are Diamond and Magnetite (Fe_3O_4) due to their good biological compatibility. The use of nanocryosurgery in the treatment and management of cancer minimizes the regenesis or reemergence of tumour cells.

4.3.2 Nanodrug delivery in cancer patients

Conventional drug delivery systems used to deliver drugs used in chemotherapy for the treatment of cancer often results in free drugs circulating in the bloodstream making it difficult to determine the accurate dosage required and at the same time having a negative effect on other healthy cells and organs due to the toxicity of the drugs involved in the treatment. To minimize the negative side effects, It is important that the drugs used in the chemotherapy be directed and be confined to the affected cells (cancerous cells). Several Nanoparticles have been developed to facilitate the delivery of drugs to cancer patients and they include; polymeric nanoparticles drug carriers, Lipid-based (liposomes and micelles) drug carriers, viral-based nanoparticles drug carriers, and carbon nanotube-based drug carriers. The use of Nanodrug carriers with magnetic nanoparticles and a magnet as a means of delivery allows for the controlled release of drugs to the affected cells and also prevents tarnishing of drugs in the gastrointestinal region.

4.3.3 Magnetic fluid hyperthermia

Cellular metabolic activity in cancer cells is greatly influenced by deviations in body temperature compared to the normal cells. Hyperthermia that works on the principle of elevation of body temperature utilizes this weakness in cancer cells to slow or stop their spread. The body temperature is raised in the range of $(40 - 44℃)$ to slow down metabolic activity in the cancer cells lowering the rate of their spread. Raising body temperature is done at three levels (local, regional, and whole-body). Raising whole-body temperature (whole-body hyperthermia) requires the use of thermal blankets and is suitable for destroying metastatic tumour cells. Partial (Regional) hyperthermia raises the temperature required to destroy locally advanced cancerous cells by utilizing the heating effect of microwave radiations. Raising the temperature to destroy cancerous cells in small affected areas (Local hyperthermia) requires the use of techniques such as radiofrequency ablation, focused ultrasound, laser ablation, and Magnetic fluid hyperthermia. Magnetic Fluid Hyperthermia works by incorporating magnetic nanoparticles (ferrofluids) that help in the transformation of magnetic energy to heat energy required for local hyperthermia. Magnetic Fluid Hyperthermia combined with the existing methods of cancer treatment (radiation therapy and chemotherapy) can be applied in the treatment of glioblastoma multiforme (brain cancer), prostate cancer, pancreatic cancer, and cervical carcinoma.

4.4 Electronic Applications

Miniaturization of electronic devices has propelled the demand for miniature electronic devices due to ease of portability and many other associated benefits. The major challenge associated with smaller electronic devices is their tendency to overheat. Developing an efficient thermal management system for these miniaturized devices is necessary to enhance their life span. Nanofluids of high thermal conductivity deployed as a coolant fluid in this thermal management system become a suitable candidate. The use of nanofluids as a coolant fluid for the next-generation electronic devices seems promising. Nguyen et al. [73] using (Al_2O_3/H_2O)-based nanofluid as a possible candidate for microprocessors cooling in electronic devices reported better cooling rates compared to base fluid alone. This was attributed to an enhanced convective heat transfer coefficient of up to (40%) as a result of the presence of (Al_2O_3) nanoparticles. Korpyś et al. [74] incorporating (CuO/H_2O) nanofluid in the commercial heat sink (ZM-WB3 Gold by Zaman) mounted on Intel Pentium 4 HT 570 J CPU, observed a decline in CPU temperature by 0.5℃ compared to the use of base fluid alone. This decline was attributed to the use of (CuO) nanoparticles in water. Jang & Choi [75] investigating the cooling performance of a microchannel heat sink containing nanofluids (Cu/H_2O) and (Diamond-water) nanofluids reported better cooling performance of microchannel heat sink containing (diamond-water)-nanofluid at a particle volume concentration of (1.0 vol.%) and particle size of 2nm compared to microchannel heat sink containing water alone.

4.5 Other Applications of Nanofluids

4.5.1 Nanomaterial based electrodes for Microbial Fuel Cell (MFC)

The MFC (or Microbial Desalination cell) serves as an alternative portable renewable energy source capable of powering low-power electronics and implantable medical devices. MFC works by converting chemical energy contained in organic compounds into electrical energy through microbial (bacterial) activity in the cell. The efficiency of MFC relies on the electrode type and electron mediator used. A study by Mehdinia et al. [76] on ($MWCNT/SnO_2$) nanocomposite material coated glassy carbon electrode (GCE) for the anode electrode in MFC cell revealed enhancement in electrochemical performance by the ($MWCNTs\text{-}SnO_2/GCE$) anode electrode compared to (MWCNTs/GCE) and bare GCE anodes with maximum densities power of 1421mWm^{-2}, 699mWm^{-2} and 457 mWm^{-2} respectively. Thepsuparungsikul et al. [77] assessing different types of CNTs-based anodes (MWCNT-COOH), (MWCNT-OH) and (SWCNT-COOH) to boost the performance of microbial fuel cell reported better power performance in (MWCNT-OH) based anode electrode filtered on poreflon membrane. The open-circuit voltage and power density attained from (MWCNT-OH) anode electrode were (0.75V) and (167mWm^{-2}) respectively which was 130% higher than plain Carbon cloth.

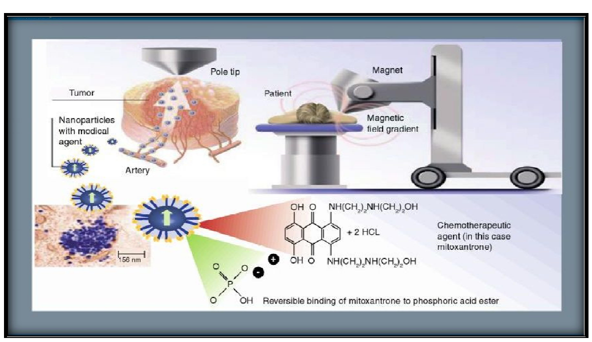

Fig. 6. Magnetic drug Delivery in cancer patients
(Figure Source: Barakat [72])

4.5.2 Nanobrake fluids

Brake failure (loss of braking) in motor vehicles can be attributed to factors such as overheating, brake pad degradation, and occurrence of vapor-lock. The occurrence of vapor-lock is connected to the properties of the brake fluid. To minimize the occurrence of vapor-lock nano-based brake fluids such as Copper-oxide (CuO) and Aluminium-oxide (Al_2O_3) based brake fluids are preferred as hydraulic brake fluids. The nanobrake fluids have a high boiling point, enhanced viscosity, and higher thermal conductivity compared to the traditional brake fluids. The higher boiling point and enhanced thermal conductivity minimize the occurrence of vapor- lock resulting from the boiling of the brake fluid caused by heat generated during braking which is important in enhancing safety while driving.

5. CONCLUSION

The current review has focused on various methods used to synthesize nanofluids, thermophysical properties, and applications of nanofluids in various fields. The future use of nanofluids in heat transfer applications is promising and therefore more needs to be done to address some of the setbacks encountered while using nanofluids as thermal transfer fluid such as agglomeration (clustering) of nanoparticles which affects the stability of the nanofluids hindering their continued use.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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