IOP Conference Series: Materials Science and Engineering

Recent Advancements in the Development of Nanofluid Technology in Heat Transfer Applications

To cite this article: O.O. Oyeleke *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1107** 012209

Recent Advancements in the Development of Nanofluid Technology in Heat Transfer Applications

O.O. Oyeleke[1], O.S. Ohunakin[1,2], D.S. Adelekan[1], O.E. Atiba[1], M.O. Nkiko[3], G. Jatinder[4]

[1]The Energy and Environment Research Group (TEERG), Mechanical Engineering Department, Covenant University, Ogun State, Nigeria

[2]Senior Research Associate, Faculty of Engineering & the Built Environment, University of Johannesburg, South Africa

[3]Department of Physical and Chemical Sciences, Elizade University, Ilara Mokin, Nigeria

[4]Department of Mechanical Engineering, Ph.D. Research scholar, IKGPTU, Kapurthala, Punjab, India

Abstract-

The development of nanofluid technology has created a niche and instigated a new area of novel researches into the enhancement of heat transmittance and transport properties of conventional working fluids with various nanoparticle types in various heat exchange applications, due to the poor thermal performance of conventional fluids. From the development of single nanofluids, to hybrid nanofluids, to the use of surface active agents and stabilizers in ensuring homogenous dispersion and chemical stability, to the use of turbulence promoters with nanofluid, all these were presented as novel developments arising from continuous investigations and study into the heat enhancement performance of different nanoparticle morphology, size, volumetric concentration etc. Thus the subject of this review work is to provide a key insight into the recent advances in the development and utilization of nanotechnology in enhancing heat transfer and transport properties by summarizing progress in the made in the development of nanofluids for the last five years.

Key words: Nanofluid, Thermal Conductivity, Heat exchangers, Surfactants

1 Introduction

The subject of heat transfer is something synonymous with our human existence, a prime case in point of this, is the fact the human body is constantly rejecting heat to the environment in tropical environments and retaining heat in a temperate regions, as such the knowledge of heat transfer also finds various applications in our modern world, as modern devices and equipment are modelled and developed on the basis of heat transfer, from, laptops, electronics, containing chips and micro-processors, to automobiles and industrial equipment in food processing, electrical and electronics, communication, biomedical industries, as well as in power plants (nuclear reactors) are all designed based on the knowledge of heat transfer [1], [2]. Rapid technological growth in the development of these industrial equipment have led to challenges of ensuring proper cooling due to the generation of higher amounts of heat. By design, electrical systems give off heat due to resistance to current flow, while mechanical systems consume energy to generate work and by nature give off heat as thermal losses (1st law of thermodynamics), which is a form of waste, that has to be dispersed to prevent thermal cyclic stresses and fatigue in the components of the system, hence the need for cooling systems such as heat exchangers such as radiators, condensers, cooling towers etc., which are selected based on the application requirements and size of the system to convey and dissipate heat from the system.

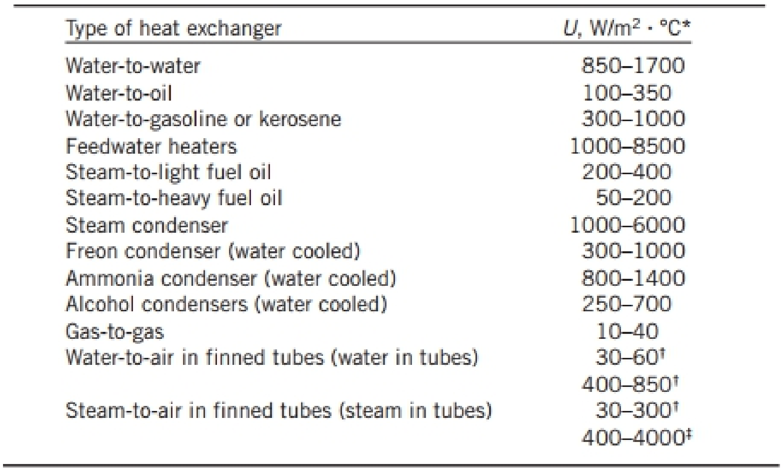
The waste heat generated in mechanical and electrical systems can be conveyed via the mechanism of convection, which involves the transfer of heat, through the bulk motion of a working fluid. Therefore, heat flow through cooling systems such as heat exchangers requires a working fluid, to effectively convey and transfer the generated waste heat out of the system. Taking the automobile industry as a case in point, the working fluid utilized by the heat exchangers (radiators) must convey up to 33% of the waste heat generated [3]. However, as the current fluids utilized (water, glycerol and ethylene glycol), have low thermal transmittance characteristics such as the thermal conductivity, which limits the heat transfer efficiency of such cooling systems, thus requiring the use of larger radiators [4]. As such, current research trends are observed to be aimed at carrying out investigations into improving the heat transfer and thermal efficiency of these cooling systems. There have been several developments towards this challenge of heat transfer efficiency in industrial applications to achieve better heat transfer performance and efficiency.

Different innovations and techniques have been utilized and implemented in the past to enhance heat transfer performance and thermal efficiency which includes: pure liquid forced convection, surface vibrations, mechanical mixing and use of extended secondary surfaces (fins, louvres and micro-channels in improving the heat transfer properties [5], [6], however, these techniques have either reached their limits, or are limited, such as secondary surfaces, due to an ever increasing heat flux requirement and complexity, as fins and louvres increase the weight and volume of the heat exchangers, while mechanical mixing requires power supply [7], [8], while others increase capital/cost of running, and require external forces [3], limiting their application. Therefore another innovative development was needed in enhancing the heat transfer, transport properties and improve the overall efficiency in the heat exchange process, focusing on developing a new type of working fluid incorporating particle fluid suspensions, utilizing particles possessing high thermal conductivity to improve the thermal properties of conventional working fluids and thus heat transfer.

However, according to [6], certain initial challenges were encountered in the use of these particle fluid suspensions, centered mainly on the size of particles (millimeter and micrometer sized) and the corrosiveness of some particles leading to issues of clogging of flow channels, rapid sedimentation, high pressure drop across flow systems and localized corrosion in some components (channels, pipelines). However, due to improvements made in the field of colloidal science, nanotechnology, and powder metallurgy, enhancing our capabilities to synthesize nanoscale materials, such as different types of nanoparticles including metallic, non-metallic, and carbon based nanoparticles, [9], these limitations were overcome. This then culminated into the development of nanofluids, which involved introducing nanometer-sized particles into the working/base fluids to improve the thermal transmittance and heat transfer characteristics of these base fluids [10], as such nanoparticles are utilized in tandem with conventional working fluids which include water, (EG) ethylene glycol, glycerol and oil, creating a new class of colloidal suspensions, with current research still ongoing in optimizing the production process and operational efficiency of these nanofluids. The subject of this review paper is to provide a key insight into the recent updates and advances in the development and use of nanofluids in various heat transfer application and heat exchange devices.

2 Heat Exchangers

Heat exchangers as the name implies, are devices utilized in the transfer of thermal energy between two different fluids at different temperatures, or between a heated surface and a moving fluid in thermal contact, or between solid particulates and a fluid. They are used essentially to facilitate the exchange of temperature from one fluid to another, while ensuring no physical mixing occurs [11]. Heat exchangers have a wide area of application, ranging from transport industry (automotive and aerospace industry), biomedical industry (cryogenics), electronics and communication, heating and air-conditioning systems, manufacturing and food processing industries (refrigeration), and power generation (nuclear reactors), and are capable of operating over a wide range of temperatures. The mechanism of heat transfer via a heat exchanger involves both conduction and convection heat transfer, convection through the hotter fluid to the wall of the separating vessel, then heat transfer by conduction, through the walls separating the two fluids, preventing mixing and convection from the wall surface through the cooler fluid [12]. Depending on the area of application, heat exchangers are used reject heat, recover heat, distill, pre-heat or cool a fluid, crystallize or regulate a process flow.



Type of heat exchanger	U, W/m^2 · °C*
Water-to-water	850–1700
Water-to-oil	100–350
Water-to-gasoline or kerosene	300–1000
Feedwater heaters	1000–8500
Steam-to-light fuel oil	200–400
Steam-to-heavy fuel oil	50–200
Steam condenser	1000–6000
Freon condenser (water cooled)	300–1000
Ammonia condenser (water cooled)	800–1400
Alcohol condensers (water cooled)	250–700
Gas-to-gas	10–40
Water-to-air in finned tubes (water in tubes)	30–60† 400–850†
Steam-to-air in finned tubes (steam in tubes)	30–300† 400–4000‡

Figure 1: Types and configuration of heat exchangers [13]

As a control device, heat exchangers consist of a number of heat transfer elements, comprising a core region which includes the surface for heat transfer, fluid distribution channels including tanks, nozzles (inlet and outlet), manifolds, headers [14]. It should be noted that all heat exchanger parts are stationary, as such there is no motion and externa heat or work interactions. The heat transfer surface (primary surface) is in direct contact with the fluids at different temperature, and prevents mixing or any form of leakage, and transfers heat via conduction heat transfer [15]. Extended secondary surfaces and appendages such as fins and louvres can also be attached to the primary surface and used to increase the surface area for heat transfer, as an increased area of contact increases the rate of heat transfer, as seen in radiators, heat sinks etc. [16], [17]. However, as stated earlier, such techniques have reached their design limit, due to an ever increasing heat flux demand, as they alternatively increase the weight and volume of heat exchangers and potentially disturb fluid flow.

There are varying types, configuration and designs of heat exchangers, depending on the area of application, fluid to fluid, solid surface and fluid, and they are classified below:

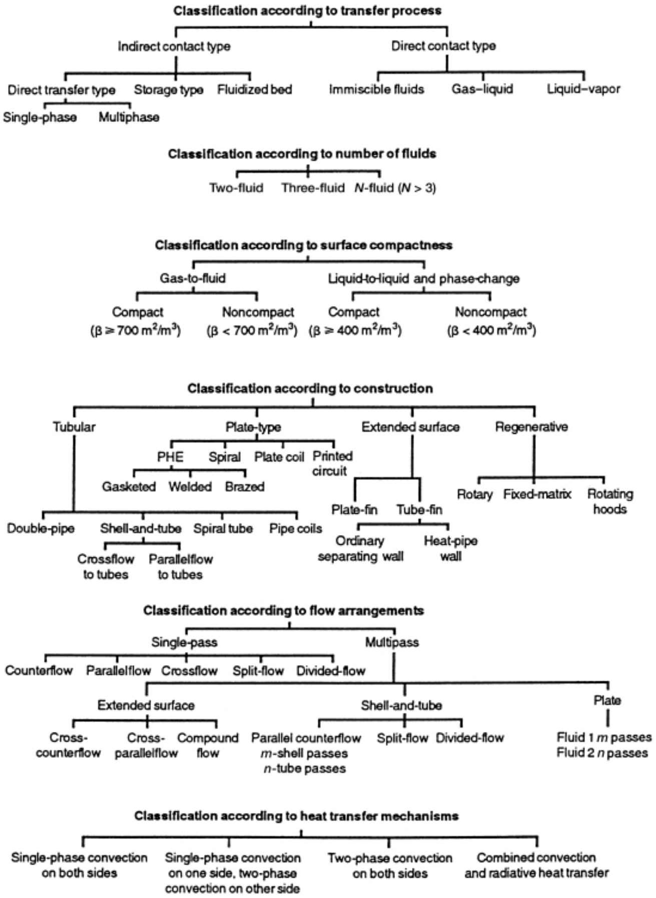


Figure 2: Classification of heat exchangers [12]

3 Nanoparticles

A **nanoparticle** (nanocrystal) is a microscopic particle that exists on a nanometer scale i.e., with at least one of its dimension less than 100nm, they possess unique physical properties such as uniformity, thermal conductance and special optical properties, while also possessing an equivalent high surface area to volume ratio. Nanoparticles are comprised of a solid core and an applied shell coating on its surface, whereby its main properties such as: magnetic, optical, electric and thermal properties, are defined by the solid core, while properties such as chemical stability, thermal resistance, hydrophilic and hydrophobic behaviour are influenced by the shell coating [6]. Shell coatings comprise two parts, a head and tail group, with the head group responsible for binding the shell coating to the core surface, through use of strong chemical bonds, ensuring stability of nanofluid properties when dispersed in a base fluid, while the tail group ensures nanoparticles are properly dispersed and homogenized in base fluid [18], [19]. Nanoparticles can be classified based on different characteristics including:

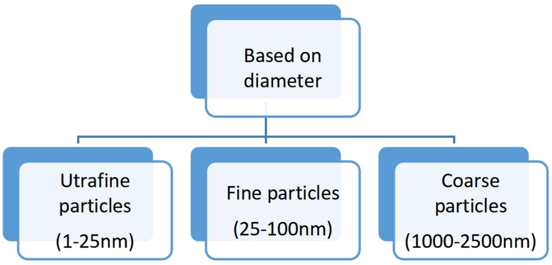


Figure 3: Classification of nanoparticles, based on diameter

In heat transfer applications, the utilization of fine particles is essential, owing to the reason that the use of larger-sized particles have been reported, leading to constraints such as: sedimentation, fouling, pressure drop across working system, clogging of channels and erosion, caused as a result of abrasion by the nanoparticles [20]. Nanoparticles can also be classified based on properties as shown in figure 2:

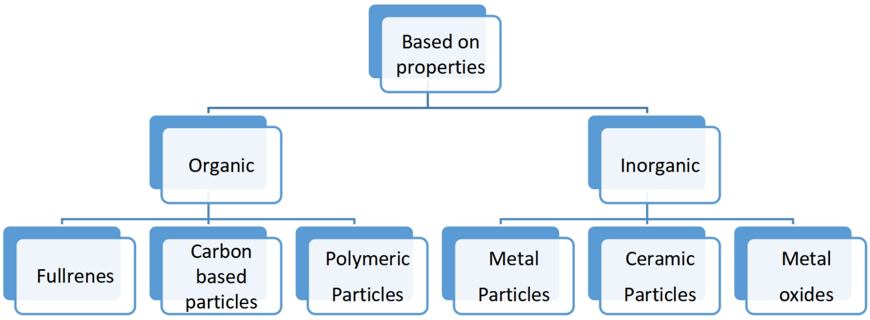


Figure 4: Classification of nanoparticles, based on properties

Commonly used core nanoparticles include: metallic particles (Fe, Ag, Au, Al and Cu), metal oxide (Al_2O_3, SiO_2, ZnO, CuO, Fe_3O_4, TiO2), nitrides (AlN, SiN), carbon based particles (nanodiamond (ND), single-walled carbon nanotubes (SWCNT), multi-walled carbon nanotubes (MWCNT), graphene nanoplatelets (GNPs), graphite), metal carbides (SiC), polymeric (nanocomposite blends containing HDPE, paraffin wax, fatty acids, etc.) as additive nanoparticles into the base fluids [21], [22]. Nanoparticles are used in enhancing the thermal and heat transfer characteristics of base fluids, and additionally are also associated with improved antibacterial activity, mass transfer and chemical reactivity [23], [24].

Nanoparticle selection in automobile cooling applications is strongly influenced by the thermal transmittance and transport properties of the material, and this is partly the reason why conventional base fluids: water (H_2O) and ethylene glycol (EG) are utilized as heat transfer fluids, having good transport properties, but the main concern for the use of ethylene glycol and water is their thermo-physical properties i.e. their low thermal conductivity. Therefore, the addition of nanoparticles to EG or the other heat transfer base fluids, increases the thermal transmittance properties and heat transfer rates of such fluids [25], with the subject of many researches having been on increasing this property, through use of different materials.

4 Nanofluids

Nanofluids (nanoparticle fluid suspensions) are colloidal suspensions containing nanometer sized particles, they are thermo-fluids designed through the dispersion of nanometer sized materials (nanoparticles, nanosheets, nanorods, nanowires, nanotubes or droplets) into a base fluid to improve thermal and fluid transport properties [6]. Nanofluids augment and confer better heat transfer properties and thermal transport properties compared with conventional fluid suspensions [26]. Suspension of nanoparticles is made possible through the interactions of the nanoparticle surface with the solvent (base fluid) being strong enough to overcome differences in density. Common heat transfer base fluids includes: water (H_2O), ethylene or tri-ethylene glycol, oil, glycerol, bio-fluids, and other prevalent fluids [27]. The aim of nano-fluids is to obtain the optimum possible thermal transmittance properties at the smallest possible volume fraction concentration ratios (preferably <1% by volume) in the base fluids.

Nanofluids can also be modified with stabilizers (surfactant or surface active agents or dispersants) aimed at ensuring long term stability and solubility, through the formation of strong chemical bonds between the nanoparticles in the base fluid and also to reduce the surface tension, examples include: Sodium Dodecyl benzene Sulfonate (SDBS), Triton X-100, Cetyl Trimethyl Ammonium Bromide and silane. Surfactants prevent aggregation, sedimentation and clustering, while ensuring complete stability of suspension when dispersed in solutions [1], [9], [22], without impacting on the thermos-physical properties (thermal conductivity). However, an excessive amount of surfactant concentration can negatively influence the thermos-physical and transport properties (surface tension) of the intended nanofluid [23]. This was confirmed by [9], who reported in the absence of surfactants, some nanofluids become non-Newtonian, characterized by increased viscosity, and formation of sediments and clusters.

In automobile cooling systems, the aim of nanofluids utilization is to enhance the efficiency of the heat removal process, thereby allowing for a reduction in the size and weight of the vehicle's cooling systems (radiator), even with the increased cooling demands of modern higher power engines, thereby allowing for reductions in overall vehicle weight, with an estimated potential enhancements in heat transfer efficiency up to 50% being possible [28], while [29], estimated that a higher temperature nanofluid could lower the radiator size approximately up to 30%, this directly translates into reduced aerodynamic drag, as well as reduced fluid pumping and fan requirements, leading to an additional 10% overall fuel savings. Therefore, the use of high thermal conductivity nanoparticles in nanofluids allow for higher temperature cooling and greater heat rejection in the automotive engines, leading to reduced size of cooling radiators, which improves fuel consumption and reduces vehicle weight.

4.1 Method of Production

The mechanism of nanofluid preparation, involves processes of production and stabilization, as nano-fluids are nanoscale colloidal suspensions comprised of condensed nanomaterials that can be produced via a **single (one) step** or **two step** methodology.

Single Step Method

The single step method of producing nanofluids involves the combination of both the production and stabilization processes in a single step, through the use of either a physical or chemical methodology in producing the nanofluids, the process is suitable for producing metallic nanofluids, owing to the fact it prevents oxidation, and occurs either a direct evaporation process, which consists of two simultaneously operations of producing and dispersing the particles in the base fluid, also known as VEROS (Vacuum Evaporation onto a Running Oil Substrate) [30], or by directly condensing metallic vapours into nanoparticles through contact with a low vapour pressurized fluid flow [6], or through a pulse wire evaporation method (PWE), these methods synthesize the nanoparticles directly into the base fluid, using this technique eliminates the sequential processes of drying, storage, transportation and dispersion. Other single step techniques include: chemical solution route, microwave assisted process, laser ablation, submerged arc nanoparticle synthesis system (SANSS) and physical vapour deposition [1], [31]. The limitation of this process arises from the fact that only low vapour pressure fluids are applicable with the process, thus can only be used for small scale nanofluid production.

Two Step Method

This is the most preferred and commonly practiced nanofluid production technique, involving the initial synthesis of nanoparticles as dry powders (fabrication), using various chemical and physical processes, such as mechanical alloying [32], deposition techniques, sol-gel process, chemical co-precipitation method etc. [1], after which stabilization occurs, in which they are dispersed into a base fluid to be sonicated and homogenized using a process of either ultrasonic agitation, chemical vapour deposition, intensive magnetic force agitation, high shear mixing, plasma treatment, to effectively homogenize, disperse and stabilize the nanoparticles in the base fluid to produce colloidal suspensions [33]. This technique is highly effective in controlling the concentration and distribution of nanoparticle dispersion in base fluid, and supports large industrial scale-up operations, due to its economic cost. However, the process is susceptible to agglomeration of nanoparticles, thus necessitating proper homogenization, and measures such as use of stabilizers such as surface active agents and pH modification to stabilize the fluid suspension [34].

4.2 Types of Nanofluid

Nanofluids can be classified as single nanofluids or hybrid nanofluids:

Single Nanofluid

This involves the use of a singular nanoparticle, dispersed and homogenized in a base fluid, consisting of any one of metallic particles, nitride, non-metallic, carbon based nanoparticles [35].

Hybrid Nanofluids

Hybrid nanofluids are a unique combination of two or more nanoparticles or nanocomposites, dispersed in a fluid suspension, hybrid nanofluids they offer advantages such as improved rheological and thermos-physical properties, through a synergistic combination/effect obtained from the combination of two chemically different nanoparticles, involving a combination of organic and inorganic nanoparticles such as metal oxide and carbon based nanoparticles, or metals and non-metals, or inorganic and phase change materials as compared to single nanofluids, which further increases heat transfer enhancement [30], [36]. Examples include: Al_2O_3-SiO_2, ND-Co_3O_4, MWCNT-Fe_3O_4, Cu-TiO_2. They can be categorized into: ceramic matrix nanocomposites, polymer matrix nanocomposite and metal matrix nanocomposites [2].

4.3 Thermo-physical Properties of Nanofluids

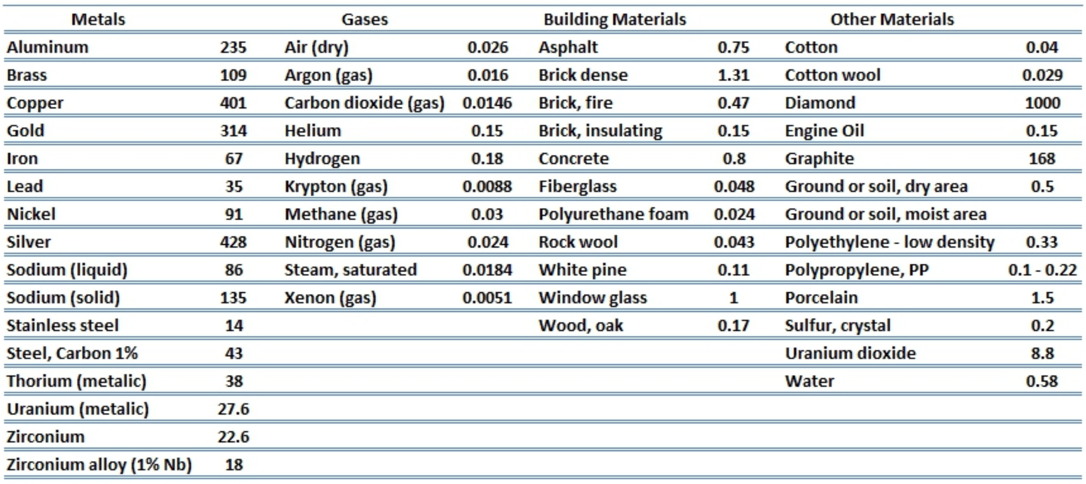
Several thermo-physical and fluid properties define the effectiveness and thermal efficiency of nanofluids including the: thermal conductivity, density, viscosity, pH content, corrosiveness, heat capacity, these depend wholly on the initial characteristics of the nanoparticles and base fluids. However, these properties are also related to each other, as increased thermal conductivity due to the addition of nanoparticles, can lead to an increase in viscosity, which in turn increases the pumping power required, which increases energy requirement and fuel consumption, thus a delicate trade-off must be ensured.

Thermal Conductivity of Nanofluid

The thermal conductivity (κ) is a property which measures a material's heat transfer characteristics, i.e. its ability to conduct heat, how much heat can be absorbed, and then dissipated by the material. Base fluids like water, EG, etc., with low thermal conductivities limit the heat transfer efficiency of cooling systems, which results in the design and use of a bigger size of radiators or heater exchangers. The use of nanoparticles such as metals and metal oxides etc., with higher thermal conductivity than the base fluids increases the thermal transmittance properties, and thus the heat transfer process [37]. The high thermal conductivity of nanofluids is also dependent on (i) the combined effect of temperature and Brownian motion; as thermal conductivity is a function of the free motion of electrons coupled with molecular vibrations, which is enhanced by particle migration and collisions due to excitation and an increase in kinetic energy (temperature), this then results in an increase in Brownian motion due to temperature (ii) interfacial layer (nanolayer) at solid-liquid interface (iii) particle morphology (iv) pH value (v) volume fraction (vii) surface area [23], [35], [9].

The influence of hybrid nanoparticle MgO-MWCNT was investigated by [37], who reported an increase in the thermal conductivity with increasing temperature and volume fraction, confirmed by [38], who also reported that thermal conductivity of nanofluids increases linearly with volumetric concentration and temperature. Therefore, the thermal conductivity of nanofluids has been observed to increase with increasing volume concentration, howbeit with an increase in viscosity, as confirmed by [39], who concluded that increased thermal conductivity by increasing the volume fraction also increases the viscosity, while it also decreases with increasing solid-liquid boundary effects, and increases with increasing Brownian motion of nanoparticles. According to [9], thermal conductivity also increases with decreasing nanoparticle size.

Experimentally, the thermal conductivity of nanofluids can be measured using temperature oscillation, thermal constants analyzer, and through the transient hot wire technique.



Metals		Gases		Building Materials		Other Materials	
Aluminum	235	Air (dry)	0.026	Asphalt	0.75	Cotton	0.04
Brass	109	Argon (gas)	0.016	Brick dense	1.31	Cotton wool	0.029
Copper	401	Carbon dioxide (gas)	0.0146	Brick, fire	0.47	Diamond	1000
Gold	314	Helium	0.15	Brick, insulating	0.15	Engine Oil	0.15
Iron	67	Hydrogen	0.18	Concrete	0.8	Graphite	168
Lead	35	Krypton (gas)	0.0088	Fiberglass	0.048	Ground or soil, dry area	0.5
Nickel	91	Methane (gas)	0.03	Polyurethane foam	0.024	Ground or soil, moist area	
Silver	428	Nitrogen (gas)	0.024	Rock wool	0.043	Polyethylene - low density	0.33
Sodium (liquid)	86	Steam, saturated	0.0184	White pine	0.11	Polypropylene, PP	0.1 - 0.22
Sodium (solid)	135	Xenon (gas)	0.0051	Window glass	1	Porcelain	1.5
Stainless steel	14			Wood, oak	0.17	Sulfur, crystal	0.2
Steel, Carbon 1%	43					Uranium dioxide	8.8
Thorium (metalic)	38					Water	0.58
Uranium (metalic)	27.6						
Zirconium	22.6						
Zirconium alloy (1% Nb)	18						

Figure 5: Thermal conductivity of chemical elements in W/mK [13]

Carbon based nanoparticles have been reported to have high aspect ratios, and the highest thermal conductivities, such as single-walled carbon nanotube, multi-walled carbon nanotube and double-walled carbon nanotube having conductivities of 6000W/mK, 3000W/mK, and 3986W/mK respectively [38], [40], as observed from figure 5, in which diamond, which is a solid form of carbon has the highest conductivity of 1000W/mK, while the metallic nanoparticles have been reported to have higher thermal conductivities than metal oxide nanoparticles [6].

Density

According to [23], who asserted that the density of the nanoparticles is a property which influences the stability of nanofluids, as well as potential agglomeration formation, while [31], indicated that increased efficiency of heat transfer process is associated with density increase. Density is measured using density meters or pycometry. According to [41], the density of nanofluids has been reported to increase with increasing volumetric weight concentration of nanofluids, and to decrease with increasing temperature.

Viscosity

The dynamic viscosity of hybrid Al_2O_3-MWCNT/thermal oil nanofluids, was studied and reported by [40], for different temperatures and volume concentrations, concluding that the nanofluid was Newtonian in its rheological behaviour, with the viscosity reported to increase with increasing nanoparticle volume concentrations in base fluid, they also asserted that by increasing the volume concentration of nanoparticles, this increases the probability of nano-clustering formations, which hinders the free movement of the oil layers, thus increasing the dynamic viscosity, this was confirmed by [42] in their work. Viscosity was also reported to decrease with increasing temperature for all ranges, due to a decrease in intermolecular forces between molecules in nanofluids, confirmed by [9].

According to [6], [37], viscosity is also closely associated with pumping power required for flow, ease of flow and pressure drop, with an increase in viscosity increases pumping power and pressure drop across a flow system. While according to [9], [43], viscosity of nanofluid is influenced by volume fraction, particle morphology, particle size, temperature, nano-layer thickness but nanoparticle type (metallic, metal oxide etc.), has no effect on viscosity, as no correlation was found. The viscosity of nanofluids is measured with devices such as a rheometer or viscometer.

pH Content

According to [27], nanofluid stability is directly influenced by its electro-kinetic characteristics, such as the pH level, therefore pH control is essential in influencing thermal properties and stability due to strong repulsive forces. According to [6], a general rule of thumb in preventing aggregation and clustering of nanoparticles in colloidal suspensions, is to synthesize nanofluids with a pH value from its isoelectric point (IEP), to this effect, [38], synthesized hybrid nanofluids (Al_2O_3-TiO_2) with pH of 3.8, far the IEP, specifically to prevent aggregation. pH value of nanofluids can be modified through the use of surface active agents, while pH control can be carried out using simple acid treatment.

Specific Heat Capacity

The specific heat capacity is a thermos-physical property which can affect the heat transfer rate in nanofluids. According to [44], specific heat capacity varies with surface area (particle size), as smaller nanoparticles have a larger surface area to volume ratio and large specific surface areas, which increases the influence of surface energy on effective specific heat capacity.

4.4 Factors Influencing Thermophysical Properties of Nanofluid

Several factors influence and affect the properties of nanofluids, including geometrical, physical and chemical properties, which influence the thermal transmittance and rheological properties.

The thermal conductivity enhancement of nanofluids depends on a variety of factors such as the thermal conductivity of base fluid itself and single phase nanoparticles [25]. Higher thermal conductivity enhancements capability of nanofluids is attained by altering the conditions affecting thermal conductivity of nanoparticles, which is possible to make nanocomposite (hybrid) material. The factors include:

- Temperature to which the nanofluid is applied to
- Volumetric fraction of nanoparticles (concentration in the solid phase) in nanofluid
- Surface area (particle size) of the nanoparticles

- Morphology (particle shape) of the nanoparticles
- Thermal conductivity of the both base fluid and the nanomaterial (metals, oxides) [45]–[47]

Temperature

Thermal conductivity as a thermo-physical property increases with temperature, thus an increase in working temperature of nanofluids, results in an increase in the thermal conductivity of the nanofluid. [48], reported that the thermal conductivity increases with increasing temperature and volume fraction. Temperature also direct influences the effect of Brownian motion and nanoparticles clustering to form aggregates [26].

Surface Area (Particle Size)

The available surface area of nanoparticles is an important factor, which affects the thermal conductivity of nanofluids, as well as other properties such as the viscosity and density. Particle size must be controlled as too large a size leads to issues of rapid sedimentation and pressure drops during flow, as observed from the previous use of millimeter and micrometer sized particles. A particle size which has a high surface area to volume ratio is ideal, and confers high surface energy in heat transfer [38], [49], while [28], [50], stated that smaller particle sizes contributes to a higher specific surface area of nanoparticles which influences their reactivity and increases the thermal conductivity of nanofluids. However, the significance of the influence of particle size in influencing thermal conductivity was also investigated by [51], who subjected two nanoparticles (Al_2O_3) of 44nm size and (TiO_2) of 12nm size to equal tests and reported that the thermal conductivity enhancement of TiO_2 was higher than Al_2O_3, concluding that the individual thermal conductivity of nanoparticles is more influential than particle size. However, using nanoparticles with high surface area still considered beneficial and enhances thermal conductivity.

Morphology (Particle Shape)

The morphology of nanoparticles plays a vital role in determining their thermo-physical properties and heat transfer effectiveness, as the shape of nanoparticles (cylindrical, spherical, platelets, bricks, hexagonal, blades), affects the heat transfer surface area [9]. According to [52], the nanoparticle morphology has a significant effect in influencing the thermal conductivity of nanofluids, this was confirmed by [49], who stated that differences in nanoparticle dimensions, leads to appreciable differences in the amount of thermos-physical property enhancement. For nanoparticles, two particular geometries are widely used and considered acceptable for use fluid suspensions, i.e. the cylindrical and spherical geometry, with the cylindrical geometry conferring a high length to diameter ratio, with the spherical geometry having high surface area to volume ratio [53], [49]. According to [6], nanofluid having nanoparticles with a spherical shape, confer increased values of thermal conductivity in comparison with the cylindrical morphology (nano-rods and nano-tubes).

Volume Fraction

The volumetric fraction/concentration of nanoparticles in a base fluid varies, as reported in research works, with volume fractions from 0.25%-10% reported across a spectrum of literature. However, it was also reported that an increase in volume fraction increases viscosity and pumping power required as reported by [37], who investigated thermal performance of MgO-MWCNT for different volume fractions 0.25-2wt%, and reported an increase in thermal conductivity and dynamic viscosity with increasing volume fraction. An increase in volume concentration/fraction has been observed to increase thermal conductivity and also viscosity, but within tolerable limits to avoid issues relating to stability involving: coagulation, agglomeration and pumping power demand due to increased viscosity [38], [54]. This was correlated also by [9], [42] who reported that use of higher volume ratio fractions increases the rate of precipitation in nanofluids.

Turbulence Promoters

The use of turbulence promoters and inserts to create turbulence and increase heat transfer characteristics was also reported by several authors [55], [56]. Inserts such as twisted tapes, wire coils, longitudinal strips, helical tapes have been reported useful in enhancing heat transfer in addition to use of nanofluids, especially in areas of reduced flow by augmenting the intensity of turbulent flows. This however, is accompanied by an increase in friction factor, though it has been reported negligible, when compared to the potential heat transfer enhancement gains [55].

4.5 Enhancement Characteristics of Nanofluid

The heat transfer enhancement of nanofluids can be summarized as:

- Nanofluids contribute to improved thermal conductivity of conventional base fluids due to micro-convection by nanoparticles
- The high thermal diffusivity of nanofluids allows for improved flow of mixing.
- Nanofluids containing nanoparticles, enhance heat transfer surface area, allowing for improved convective heat transfer, and thus greater heat transfer.
- Large surface area to volume ratio enhances reactivity and allows for greater heat transfer.
- Nanofluids have allowed for miniaturization and reduced dimensions of traditional heat exchangers to more compact and lighter heat exchangers, saving overall vehicle weight and size (Sandhya et al. 2016).
- The use of nanofluids increase the flow turbulence which increases heat transfer and reduces pumping requirements, although this is a trade-off as the increased viscosity demands more pumping power [27], [44].

4.6 Challenges Encountered In the Development of Nanofluids

The identified challenges associated with the use of nanofluids, revolve around the use of proper utilization of standard preparation techniques, leading to issues of bi-phasic heat transfer, chemical instability, oxidation of metallic nanoparticles and sedimentation majorly arise due to gremlins in the preparation processes and oxidation of metallic nanoparticles [30]. Other

challenges include: aggregation (clustering), in which nanoparticles with high surface areas bind together forming micrometer sized particles [1], agglomeration which reduces the thermal conductivity of nanofluids, excessive volume fractions of nanoparticles in base fluid limiting total diffusivity and leading to uneven dispersion of nanoparticles.

4.7 Perspectives on Recent Works on Heat Transfer Enhancement of Nanofluids

[23], studied the stability, rheology and thermal performance of oleic acid coated alumina dispersed in a thermal-oil base fluid, the nanoparticle volume fractions were varied between 0.5-3 wt% between temperatures of 290K-330K. Alumina nanoparticles, of 40nm diameter was utilized, with oleic acid being used as a surface active agent to stabilize the nanoparticles during the dispersion process, and the nanofluid was produced using the two-step method using an ultrasonic bath and ultrasonic homogenizer for 25min. Nanofluid stability was observed increased, up to a one month duration. The thermal conductivity increased from 0.129W/mC to 0.15W/mC, a 14% increase, as well as density increased from 852kg/m^3 to 870kg/m^3, howbeit with increase in particle concentrations, and decreased with increase in temperature.

[20], investigated the heat transfer performance of hybrid and single nanofluid in a coiled heat exchanger, under laminar flow operating conditions, using hybrid silver-alumina (Ag-Al_2O_3) nanoparticles, (97.5% Alumina and 2.5% silver), of 80nm diameter and single nanoparticle Al_2O_3, of 55nm diameter, with varying volume concentration of 0.1-0.4wt%, and water (H_2O), was utilized as the base fluid at constant temperature of 368K. The nanofluids were prepared using the sol-gel single step methodology. The reported highest enhancement in the heat transfer rate was observed using the hybrid nanofluid for 0.4 % volume concentration at 31.58%, while the accompanying highest thermal performance factor was 2.55, with an increase (28.42%) in Nusselt number 4687, leading to an overall increase of 25% in thermal performance compared to base fluid.

[37], conducted experimental and theoretical investigations on the influence of hybrid nanoparticles (MgO-MWCNT), with MgO of 30nm diameter, and MWCNT of 25nm diameter, on heat transfer efficiency and pumping power, using thermal oil as base fluid between temperatures of 298K and 323K. The MgO-MWCNT hybrid nanofluid 80% MgO and 20% MWCNT, was produced using the two step methodology involving intensive magnetic force agitation for 120min and ultrasonic agitation for 60min in producing six different volume fractions of 0.25%, 0.5%, 1%, 0.75%, 1.5% and 2wt%. They reported an increase in dynamic viscosity with an increase in volume fraction up to 65% at 2wt% and 313K, while thermal conductivity increased with rising temperature and volume concentrations up to 62% at 2wt% volume fraction and 323K, however an increase in pumping power up to 75% in laminar flow and 20% in turbulent flow was reported due to the increase in viscosity.

[57], carried out experimental investigations into the thermal performance of nanofluid enhanced refrigerants (TiO_2, SiO_2, Al_2O_3) for improved performance in a domestic refrigeration system using LPG as the base fluid and standard. Nanofluid comprised of TiO_2 (15nm), SiO_2 (5-15nm) and Al_2O_3 (13nm) were produced using the two-step methodology comprising 40g optimum mass charge of LPG with 0.2g/L volume fraction of nanoparticles using ultrasonication. They reported improved evaporator air temperature for all nanofluids compared to pure LPG at same pull down time, with a maximum of -9C for SiO_2 at 180min PDT, while in terms of power consumption, both SiO_2 and TiO_2, showed improvements of 13% and 12% respectively compared to base fluid, with the exception of Al_2O_3, which consumed more power. An improvement in co-efficient of performance (COP) of 2.06% was also reported using both SiO_2 and TiO_2, while Al_2O_3 reduced COP by as much as 31.96%. However, in terms of thermal

conductivity, a reduction was reported at suction side of 2.61% for SiO_2, and 1.97% for both TiO_2 and Al_2O_3, while an increase was reported at the discharge side of 0.45% and 2.75% for SiO_2 and TiO_2 respectively, while Al_2O_3 equaled the base fluid. In terms of viscosity the values largely remained unchanged across both nanofluid and base fluid at suction site and increased with nanofluid at discharge site, increasing by 0.99% and 6.09% for SiO_2 and TiO_2 respectively and remained unchanged for Al_2O_3.

[39], investigated the heat transfer phenomena and pressure drop across a corrugated-plate heat exchanger using single and hybrid nanofluids consisting (Ag, MWCNT, Ag-MWCNT). The nanoparticles were MWCNT of 10-20nm diameter, silver (Ag) of 35nm diameter, while water (H_2O), was used as the base fluid, and the final nanofluid was produced using the two-step method utilizing ultra-sonication with stirring for 24hr.The nanoparticle volume concentrations ranged from 0.5-1.0wt%, and the applied temperature range from 283K to 353K, the influence on thermal conductivity and viscosity were studied. The Maximum enhancement in thermal conductivity occurred using 1% volume fraction of Ag-MWCNT at 353K giving 0.871W/mK, an increase of 30.2%, as compared to base fluid, while the viscosity at conditions were obtained as 1.33mPa, an increase of 12%, compared to the base fluid viscosity at 353K, while the overall heat transfer enhancement at 1% Ag-MWCNT was reported 41.3%. It was also concluded that an increase in volume fraction increased the Nusselt number, which corresponds to an increase in Peclet number, while friction factor (pressure drop) decreased with increasing Peclet number

[56], carried out the heat transfer enhancement of Al_2O_3 and ethylene glycol (EG) nanofluid with and without wire-coil inserts in an automobile radiator, with varying volume concentrations of 0.08%, 0.5% and 1%wt investigated. The nanofluid was prepared using the two-step method, involving ultrasonic agitation for 30min, utilizing Al_2O_3 nanoparticles of 40nm diameter, and sodium dodecyl-benzene sulfonate (SDBS) as surfactant, to stabilize the dispersion during preparation. The wire coil inserts made of copper having high conductivity of 0.3mm thickness and 0.013m width were utilized. The use of wire coil showed an increase in thermal performance of 9% for Reynolds number up to 22,672, and also increased the friction factor. Thermal performance enhancement of 14% was reported using both Al_2O_3 nanofluid and wire coil at Reynolds number of 22672.

[36], investigated the characterization and thermal performance assessment of a novel hybrid (ZnO) and encapsulated parrafin wax nanofluid for use in energy related applications, the base fluid utilized was a combination of propylene-glycol-water mixture. The volume concentrations were 0.5-2wt% for ZnO nanoparticles, and 4-16wt% for paraffin wax. The study showed increased thermal enhancement characteristics with thermal conductivity increased by 10.4%, and specific heat of the nanofluid increased by 18.7%, when compared with the base fluids, while the maximum increase in heat transfer rate was reported 13.54%.

[38], conducted experimental investigations and model development into the thermal conductivity enhancement of Al_2O_3-TiO_2 hybrid nanofluid, using water as a base fluid. Nanofluids consisting of 20nm Al_2O_3 and TiO_2 particles and water as base fluid were produced using the two step method using ultrasonication for 40 min, to produce 5 nanofluids with different proportions of TiO_2 and Al_2O_3 (S1{1%Al_2O_3}, S2(0.25:0.75), S3(0.5:0.5),

S4(0.75:0.25), S5{1%TiO_2}) making up an overall 1% volume fraction. The pH was maintained at 3.8, far from the IEP to prevent aggregation. The thermal conductivity of the nanofluids were measured at 298K, utilizing the transient hot-wire technique. The improvements in thermal conductivity was reported non-linear, for reasons of nanofluid stability with formation of agglomerates and sediments, with a maximum thermal conductivity increase of 47%, obtained from the most stable nanofluid S1.

[3], investigated the reliability of nanofluid volumetric fraction on heat transfer characteristics (thermal and transport performance) of an automobile radiator, using two nanofluids, (Al_2O_3/water) and (CuO/water). The volume concentrations adopted were 1%, 3%, 5% and 7wt% of nanoparticles at 353K temperature under laminar flow of 1750 reynolds number. Thermal performance enhancement increased with the use of nanofluids, with an increase of 38% with CuO, and 45% for Al_2O_3. They concluded that improvements in heat transfer performance could lead to sizeable reductions in radiator volume, howbeit with an increased pumping power due to pressure drop.

[40], investigated the experimental and theoretical heat transfer efficiency of Al_2O_3-MWCNT/thermal oil hybrid nanofluid in cooling systems, using Al_2O_3 (20nm) and MWCNT (20-30nm) nanoparticles, over different temperatures from 298K to 323K, using varying nanoparticle volume fractions from 0.125%, 0.25%, 0.5%, 0.75%, 1% and 1.5wt%. The hybrid nanofluid was produced using the two-step methodology, involving ultrasonic agitation for 60min and magnetic force agitation for 120min, without the use of surface active agents. The highest enhancement in thermal conductivity of 45% was obtained at 323K and 1.5wt% volume fraction, while for dynamic viscosity a minimum increase of 15% was obtained at 0.125wt% and 323K, and a maximum increase of 81% at 1.5% and 313K, leading to a maximum and minimum increase in pumping power of 63% and 14% respectively. While the maximum increase in heat transfer efficiency of the nanofluid was 56%, at 323K, and 1.5% volume fraction.

[58], carried out the performance evaluation of SiO_2/mineral oil (LPG) enhanced nanofluid in domestic refrigerant for improved performance compared to conventional R134A refrigerant. Nanofluid containing LPG, comprising (60:40) propane-butane in mass charges of 10g, 50g and 70g and SiO_2 nanoparticles of 5-15nm size, in concentrations of 0.2g/L, 0.4g/L and 0.6g/L were prepared using the two-step methodology involving ultrasonication. They reported improvements in evaporator and compressor heat transfer performances in terms of pull down time, evaporator air temperature, up to -11C at 40g LPG-0.4g/L SiO_2, and discharge temperatures ranging from 1.43%-20%, with the lowest being 56C at 50g LPG-0.2g/L SiO_2, this was also coupled with an increase in co-efficient of performance (COP) compared to R134A, with COP values ranging from 2.05 at 50g LPG-0.4g/L SiO_2 to 2.65 at 60g LPG/0.2g/L SiO_2, as well as enhancements in cooling capacity up to 210.59W, an improvement of 7.47% using 60g LPG-0.2g/L SiO_2 when compared to R134A. Enhancements in power consumption were also recorded for compressor up to 64W using 50g LPG-0.4g/L (SiO_2) an improvement of over 25%, while an improvement in thermal conductivity (>40%) and viscosity (>31%) was also reported at both suction and discharge sites, compared to R134A.

[53], investigated the thermal performance of MWCNT nanofluid for use in automobile radiator, as well as the influence of fluid flowrate on thermal performance, using MWCNT nanoparticles of 20nm. Water (H_20) was utilized as the base fluid. Volume fraction of 0.1wt% was adopted for nanoparticle concentration for 180min, to prevent agglomeration. The nanofluid production

process adopted was the two-step methodology involving an ultrasonic bath. Mass flow rate utilized varied from 0.5l/min to 2.5l/min. Maximum thermal conductivity enhancement was obtained at 0.92W/mK, while the overall improvement in thermal performance using the nanofluid was reported up to 45%, when compared to base fluid. The variability of flow rate indicated that at lower flow rate, higher thermal performance of 8% was obtained, as opposed to higher flow rate.

[59], conducted the energetic analysis of TiO_2-LPG nano-refrigerants to replace R134A in a conventional refrigerant system experimentally and using ANN. The influence of nanofluid was modelled using ANN, as well as studied experimentally and compared to R134A base fluid. LPG (Capella D-type mineral oil) was utilized as the base fluid in mass charges of 40g-70g, while the volumetric concentration of TiO_2 nanoparticles of 15nm size were 0, 0.2, 0.4, and 0.6g/L, the nanofluids were then prepared via the two-step methodology involving intensive magnetic agitation for 10hours and ultrasonication for 15hours. Experimentally, they reported gains in the cooling capacity and co-efficient of performance (COP) of 18.74-32.72% and 10.15-61.49% respectively, while energetic factors such as compressor power consumption and pressure ratio were also reduced, compared to those of R134A in the range of 3.20-18.1% and 2.33-8.45% respectively, while the isentropic efficiency was increased by 1.56-10.23%. It was observed that the optimum thermal and energetic performance was obtained from using 40g LPG with 0.4g/L TiO_2 nanofluid concentrations, and that a lower compressor discharge temperature and pressure was obtained using nanofluids. Results from ANN modelling was reported to correlate with experimental results with an R^2 value of 0.914-0.970, a RMSE value ranging from 0.111-2.317 and a MAPE from 0.865-3.148%.

[9], conducted an investigation on the influence of TiO_2 nanofluid in enhancing the heat transfer performance of automobile radiators, using water (H_2O) as the base fluid. TiO_2 nanoparticles of 44nm was used in nanoparticle volumetric concentrations of 0.1%, 0.2% and 0.3wt%. The nanofluid was produced using the two-step methodology using ultrasonication, with the addition of surfactant Triton X-100 to ensure stability. The flowrates used in the automobile radiators were $0.097m^3/h$ and $0.68m^3/h$ for laminar flow between 560 and 1650 Reynolds number, while the temperature range was from 298K to 358K. Maximum heat transfer obtained was $2050W/m^2k$, at 0.3wt% volume fraction, an enhancement of up to 47%.

[60], investigated and compared the experimental and theoretical thermal transmittance enhancement of SiO_2 nanofluid and SiO_2-Cu hybrid nanofluids, using water (H_2O) and ethylene glycol (EG) as the base fluids. Nanoparticles of SiO_2 of 75nm size were modified with deposited Cu nanoparticles of 10nm size, on the particle surface. The nanofluid was synthesized using the two-step methodology using intensive magnetic force agitation for 180min and then ultrasonication for 120min. Nanoparticle volumetric concentrations of 0.5% and 1wt% were used in preparing nanofluid. The applied temperature range was from 298K to 313K. Thermal conductivity enhancement of SiO_2 in both water and EG, was about 2%, while thermal conductivity enhancement of SiO_2-Cu increased by 11% for water, and 11.5% for EG.

[42], investigated the thermal transmittance properties of a Cu/engine oil nanofluid.

Nanoparticles of Cu of 50nm diameter were used. The nanofluid was produced using the one step methodology of electrical explosion of wire (EEW), using nanoparticle volume fractions of 0.2%, 0.5% and 1wt%. The applied temperature range was from 313K to 373K. The maximum improvement in thermal conductivity for 0.2%, 0.5% and 1wt% nanofluids were 27%. 32% and

49% respectively, and were observed to increase with temperature and volume fraction as established, while the highest possible enhancement in viscosity was 37% obtained at 1wt% concentration.

[55], studied the effect of MWCNT-Fe_3O_4 hybrid nanofluids on the heat transfer properties and friction factor, with and without the use of longitudinal strip inserts, using water as the base fluid. The nanofluids were produced using the two step methodology, using cylindrical MWCNT nanoparticle (26%) of 20nm diameter modified with Fe_3O_4 nanoparticles (74%), nanoSperse AQ surfactant was added to ensure complete stability of nanofluid. The nanofluids were tested for heat transfer enhancements and friction factor at 3000-22000 Reynolds number, nanoparticle volume fraction used was from 0.1%-0.3wt%, while longitudinal strips o aspect ratios 1, 2, 4, and 12 were utilized. The applied temperature range was between 298K and 313K. Maximum heat transfer enhancements were obtained for 0.3% volume fraction without strip inserts at 32.72%, while maximum enhancement with strip inserts at 0.3% vol. fraction and strip inserts of 1 aspect ratio was 50.99% at 22000 Reynolds number, while friction factor increased by 15% using the nanofluid.

[61], investigated the energetic and exergetic performance analysis of TiO_2, SiO_2, and Al_2O_3/LPG nanofluid with lubricants (polyol-ester (POE), and mineral oil) in a conventional refrigeration system compared to R134A/POE refrigerant. LPG was used as the base fluid with an optimum mass charge volume of 40g, three nanoparticles TiO_2 of 15nm size, SiO_2 of 5-15nm size and Al_2O_3 of 13nm size were utilized. The lubricants utilized were mineral oil (Capella MO) and polyol-ester. The nanofluids were produced via the two-step methodology involving intensive magnetic force agitation for 10hours and ultrasonication for 15hours with 0.2g/L volume fraction of nanofluid with 1litre lubricant. They concluded that optimum energetic and exergetic performance was obtained using 0.2g/L TiO_2-LPG nanofluids, with increased efficiency in terms of compressor power consumption and system irreversibility of 15.87% and 31.69% respectively, while in terms of co-efficient of performance (COP), maximum increase was reported of 56.32%, with a further increase of 47.06% was reported for second law efficiency

[31], investigated the thermal enhancement properties of boron nitride (BNNT) in (CSP) concentrated solar thermal heat exchange applications. The base fluid utilized was the thermal oil from the CSP plant which contains biphenyl (26.5%) and diphenyl oxide (73.5%). The applied temperature range was from 303K to 363K. The two step methodology was used in producing the nanofluid involving the process of magnetic force agitation for 30min and ultrasonication for 4hours, using BNNT nanoparticles of 20-30nm, and Triton X-100, was used as surfactant. The nanoparticle volume fraction utilized were 3.4%, 5.8%, and 8.6%. An increase in temperature and volume fraction was observed to increase the thermal conductivity, with a maximum increase in thermal conductivity of 33% at 8.6%, maximum increase in viscosity was ascertained at 6%, compared to base fluid, while overall enhancement of heat transfer was measured at 18% of BNNT nanofluid at 363K and 8.6% volume concentration.

[62], investigated the performance enhancement properties of LPG refrigerant with varying concentrations of TiO_2 nano-lubricants mass charges (LPG-TiO_2) for improved performance. LPG with concentrations varied from 40g, 50g, 60g and 70g and TiO_2 nanoparticles/oil concentrations varied from (0.2g/L, 0.4g/L, 0.6g/L), were utilized in a 50L R134A refrigerant compressor. Nanofluids were prepared using TiO_2 nanoparticles of 15nm size, using the two-step

methodology involving ultra-sonication. They reported a reduction in overall power consumption and compressor energy consumption using nanofluids, with lowest power consumption of 44W at 50g LPG and 0.2g/L TiO_2, a reduction of over 13%, lowest compressor power consumption of 21W at 70g LPG and 0.2-0.4g/L (TiO_2), an over 70% increase, also, an increased cooling index capacity using nanofluid enhanced refrigerants was observed, with a maximum cooling capacity index of 65W at 70g LPG and 0.6g/L TiO_2, an increase of over 16%, while the maximum co-efficient of performance (COP) of 2.8, obtained from 40g LPG with 0.4g/L (TiO_2), an increase of over 12% using a pure LPG refrigerant as control standard.

5. Conclusion

A comprehensive review of the recent advances and developments in the field of nanofluids is presented in this paper, with specific focus on heat transfer properties and applications, ranging from the deployment of nanofluids in heat exchangers, refrigerants, for improving the thermal exchange properties and heat transfer efficiency. It was observed that heat transfer can be improved up to 30% by utilizing nanofluids in various applications. More recent trends in the development of nanofluids indicates a refinement in the production process, a proper understanding of the mechanism of preparation of single and hybrid nanofluids, as well as the emergence of turbulence promoters and inserts such as wire coils, longitudinal strips, twisted tapes, helical tapes etc. in tandem with nanofluids in augmenting and enhancing heat transfer characteristics of nanofluids. As a rule of thumb, heat transfer enhancement is a trade-off between thermal conductivity and viscosity, with increased viscosity leading to increase pumping power requirements, however, it was concluded that use of nanofluid as alternative to base fluid is not ideal, if the increase in viscosity of the nanofluid is more than four times greater than the increase in thermal conductivity enhancement, else it can be utilized.

Stability and homogenous dispersion of nanofluids can be ensured using surface active agents (surfactants) to stabilize the fluid suspensions, stability can also influenced by pH value, which can be modified to ensure pH is far from IEP point. In using flowrates to actuate the heat transfer process, there are limitations, as excessively turbulent flow rates could lead to issues of erosion on radiator (cooling system) tube surface, as well as issues of aeration and foam formation of radiator coolants, especially for hydrophobic nanofluids with surfactants added, which reduces heat transfer efficiency.

Reference

[1] R. B. Ganvir, P. V Walke, and V. M. Kriplani, “Heat transfer characteristics in nanofluid — A review,” *Renew. Sustain. Energy Rev.*, vol. 75, no. October 2016, pp. 451–460, 2017.

[2] G. Huminic and A. Huminic, “International Journal of Heat and Mass Transfer Hybrid nanofluids for heat transfer applications – A state-of-the-art review,” *Int. J. Heat Mass Transf.*, vol. 125, pp. 82–103, 2018.

[3] I. Elbadawy, M. Elsebay, M. Shedid, and M. Fatouh, “Reliability of nanofluid concentration on the heat transfer augmentation in engine radiator,” *Int. J. Automot. Technol.*, vol. 19, no. 2, pp. 233–243, 2018.

[4] J. A. R. Babu, K. K. Kumar, and S. S. Rao, “State-of-art review on hybrid nanofluids,” *Renew. Sustain. Energy Rev.*, vol. 77, no. March, pp. 551–565, 2017.

[5] M. Elsebay, I. Elbadawy, M. H. Shedid, and M. Fatouh, “Numerical Resizing Study of Al2O3 and CuO Nanofluids in the Flat Tubes of a Radiato,” *Appl. Math. Model.*, 2016.

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

[7] M. Bahiraei, R. Rahmani, A. Yaghoobi, E. Khodabandeh, and R. Mashayekhi, “Recent research contributions concerning use of nano fl uids in heat exchangers : A critical review,” *Appl. Therm. Eng.*, vol. 133, no. January, pp. 137–159, 2018.

[8] A. S. Tijani and A. Suhail, “Thermos-physical properties and heat transfer characteristics of water / anti-freezing and Al 2 O 3 / CuO based nanofluid as a coolant for car radiator,” *Int. J. Heat Mass Transf.*, vol. 118, pp. 48–57, 2018.

[9] S. Ali, M. Ozkaymak, A. Sözen, T. Menlik, and A. Fahed, “Improving car radiator performance by using TiO2 -water nanofluid,” *Eng. Sci. Technol. an Int. J.*, 2018.

[10] M. Beriache *et al.*, “Experimental study on thermal performance of MWCNT nanocoolant in Perodua Kelisa 1000cc radiator system ☆,” *Int. Commun. Heat Mass Transf.*, vol. 76, pp. 156–161, 2016.

[11] B. Zohuri, “Heat Exchanger Types and Classifications,” in *Compact Heat Exchangers*, 2017, pp. 19–56.

[12] Bahmanz, “Classification of Heat Exchangers,” 2001, pp. 1–77.

[13] Y. A. Cengel, “A Practical Approach.”

[14] A. M. Hussein, “Thermal performance and thermal properties of hybrid nanofluid laminar flow in a double pipe heat exchanger,” *Exp. Therm. Fluid Sci.*, 2017.

[15] R. K. Shah, B. Thonon, and D. M. Benforado, “Opportunities for heat exchanger applications in environmental systems,” vol. 20, pp. 631–650, 2000.

[16] S. Sumanth, V. Krishna, W. X. Shen, and L. W. Zhang, “Performance analysis of automobile radiator using carboxyl graphene nanofluids Performance analysis of automobile radiator using carboxyl graphene nanofluids,” in *Material Science and Engineering*, 2018.

[17] S. H. Habibian, A. M. Abolmaali, and H. Afshin, “Numerical Investigation of the effects of fin shape, antifreeze and nanoparticles on the performance of compact finned-tube heat exchangers for automobile radiator,” *Appl. Therm. Eng.*, 2018.

[18] X. Li, W. Chen, and C. Zou, “The stability, viscosity and thermal conductivity of carbon nanotubes nanofluids with high particle concentration: A surface modification approach,” *Powder Technol.*, 2019.

[19] V. Kumar and R. Rekha, “Exergy and energy performance for wavy fin radiator with a new coolant of various shape nanoparticle - based hybrid nanofluids,” *J. Therm. Anal. Calorim.*, no. 0123456789, 2020.

[20] H. R. Allahyar, F. Hormozi, and B. Zarenezhad, “Experimental investigation on the thermal performance of a coiled heat exchanger using a new hybrid nanofluid,” *Exp. Therm. FLUID Sci.*, 2016.

[21] N. Nasajpour, D. Toghraie, and M. Afrand, “A new correlation for predicting the thermal conductivity of ZnO – Ag (50 % – 50 %)/ water hybrid nano fl uid : An experimental study,” *Powder Technol.*, vol. 323, pp. 367–373, 2018.

[22] M. U. Sajid and H. M. Ali, “Thermal conductivity of hybrid nanofluids : A critical review,” *Int. J. Heat Mass Transf.*, vol. 126, pp. 211–234, 2018.

[23] S. Ilyas, R. Pendyala, M. Narahari, and L. Susin, “Stability , rheology and thermal analysis of functionalized alumina- thermal oil-based nanofluids for advanced cooling systems,” *Energy Convers. Manag.*, vol. 142, pp. 215–229, 2017.

[24] C. Selvam, R. S. Raja, D. M. Lal, and S. Harish, “Overall heat transfer coefficient improvement of an automobile radiator with graphene based suspensions,” *Int. J. Heat Mass Transf.*, vol. 115, pp. 580–588, 2017.

[25] M. Vafaei, M. Afrand, N. Sina, R. Kalbasi, and F. Sourani, “Evaluation of thermal conductivity of MgO-MWCNTs / EG hybrid nano fl uids based on experimental data by selecting optimal arti fi cial neural networks,” *Phys. E Low-dimensional Syst. Nanostructures*, vol. 85, pp. 90–96, 2017.

[26] M. Gupta, V. Singh, R. Kumar, and Z. Said, “A review on thermophysical properties of nanofluids and heat transfer applications,” *Renew. Sustain. Energy Rev.*, vol. 74, no. February, pp. 638–670, 2017.

[27] N. Azwadi, C. Sidik, M. Noor, W. Mohd, and R. Mamat, “Recent advancement of nanofluids in engine cooling system,” *Renew. Sustain. Energy Rev.*, vol. 75, no. October 2016, pp. 137–144, 2017.

[28] D. D. Kumar and A. V. Arasu, “A comprehensive review of preparation , characterization , properties and stability of hybrid nano fl uids,” *Renew. Sustain. Energy Rev.*, vol. 81, no. August 2016, pp. 1669–1689, 2018.

[29] S. Lee, S. Choi, S. Li, and J. Eastman, “Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles,” *J. Heat Transfer*, vol. 121, no. May, 1999.

[30] N. Azwadi, C. Sidik, M. Mahmud, W. Mohd, A. Aziz, and I. Muhammad, “A review on preparation methods, stability and applications of hybrid nanofluids,” *Renew. Sustain. Energy Rev.*, vol. 80, no. January 2016, pp. 1112–1122, 2017.

[31] G. Roberto, P. Estell, and J. Navas, “Boron nitride nanotubes-based nanofluids with enhanced thermal properties for use as heat transfer fluids in solar thermal applications,” *Sol. Energy Mater. Sol. Cells*, vol. 205, no. January 2019, 2020.

[32] S. Koçak, İ. Atmaca, M. Asiltürk, and A. Doğan, “Improving heat transfer performance of an automobile radiator using Cu and Ag doped TiO 2 based nanofluids,” *Appl. Therm. Eng.*, vol. 157, no. March, 2019.

[33] M. F. Nabil, W. H. Azmi, K. A. Hamid, R. Mamat, and F. Y. Hagos, “An experimental study on the thermal conductivity and dynamic viscosity of TiO 2 -SiO 2 nano fl uids in water : Ethylene glycol mixture,” *Int. Commun. Heat Mass Transf.*, vol. 86, pp. 181–189, 2017.

[34] D. G. Subhedar and B. M. Ramani, “Experimental Investigation of Heat Transfer Reference : To appear in : Case Studies in Thermal Engineering Experimental Investigation of Heat Transfer Potential of Al 2 O 3 / Water-Mono Ethylene Glycol Nanofluids as a Car,” *Case Stud. Therm. Eng.*, 2017.

[35] M. Hafiz, N. Azwadi, C. Sidik, T. Lit, R. Mamat, and G. Najafi, “Factors affecting the performance of hybrid nanofluids : A comprehensive review,” *Int. J. Heat Mass Transf.*, vol. 115, pp. 630–646, 2017.

[36] M. N. Chandran, S. Manikandan, K. S. Suganthi, and K. S. Rajan, *Novel hybrid nanofluid with*

tunable specific heat and thermal conductivity: Characterization and performance assessment for energy related applications. Elsevier Ltd, 2017.

[37] M. Asadi, A. Asadi, and S. Aberoumand, “An experimental and theoretical investigation on the effects of adding hybrid nanoparticles on heat transfer efficiency and pumping power of an oil-based nanofluid as a coolant fluid,” *Int. J. Refrig.*, 2018.

[38] A. A. Charab, S. Movahedirad, and R. Norouzbeigi, “Thermal conductivity of Al2O3 + TiO2/water nanofluid : Model development and experimental validation,” *Appl. Therm. Eng.*, vol. 119, pp. 42–51, 2017.

[39] M. Goodarzi *et al.*, “Investigation of heat transfer and pressure drop of a counter flow corrugated plate heat exchanger using MWCNT based nanofluids,” *Int. Commun. Heat Mass Transf.*, 2015.

[40] A. Asadi, M. Asadi, A. Rezaniakolaei, L. Aistrup, and M. Afrand, “Heat transfer efficiency of Al 2 O 3 -MWCNT / thermal oil hybrid nanofluid as a cooling fluid in thermal and energy management applications : An experimental and theoretical investigation,” *Int. J. Heat Mass Transf.*, vol. 117, pp. 474–486, 2018.

[41] A. O. Borode, N. A. Ahmed, and P. A. Olubambi, “Nano-Structures & Nano-Objects A review of heat transfer application of carbon-based nanofluid in heat exchangers,” *Nano-Structures & Nano-Objects*, vol. 20, p. 100394, 2019.

[42] S. Aberoumand and A. Jafarimoghaddam, “Experimental study on synthesis, stability, thermal conductivity and viscosity of Cu-engine oil nanofluid,” *J. Taiwan Inst. Chem. Eng.*, vol. 0, pp. 1–8, 2017.

[43] N. Zhao, S. Li, and J. Yang, “A review on nano fl uids : Data-driven modeling of thermalphysical properties and the application in automotive radiator,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 596–616, 2016.

[44] S. Eiamsa-ard, K. Kiatkittipong, and W. Jedsadaratanachai, “Engineering Science and Technology , an International Journal Heat transfer enhancement of TiO 2 / water nano fl uid in a heat exchanger tube equipped with overlapped dual twisted-tapes,” *Eng. Sci. Technol. an Int. J.*, vol. 18, no. 3, pp. 336–350, 2015.

[45] B. Wei, C. Zou, X. Yuan, and X. Li, “Thermo-physical property evaluation of diathermic oil based hybrid nanofluids for heat transfer applications,” *Int. J. Heat Mass Transf.*, vol. 107, pp. 281–287, 2017.

[46] G. Oliveira, E. Cardenas Contreras, and E. B. Filho, “Experimental study on the heat transfer of MWCNT/water nanofluid flowing in a car radiator,” *Appl. Therm. Eng.*, 2016.

[47] M. Hemmat, S. Esfandeh, S. Saedodin, and H. Rostamian, “Experimental evaluation , sensitivity analyzation and ANN modeling of thermal conductivity of ZnO-MWCNT / EG-water hybrid nanofluid for engineering applications,” *Appl. Therm. Eng.*, vol. 125, pp. 673–685, 2017.

[48] N. Azwadi, C. Sidik, M. Noor, W. Mohd, and R. Mamat, “A review on the application of nanofluids in vehicle engine cooling system ☆,” *Int. Commun. Heat Mass Transf.*, vol. 68, pp. 85–90, 2015.

[49] I. Nalman, D. Ramasamy, and K. Kadirgama, “Effect of nanocellulose with ethylene glycol for automotive radiator application,” in *Material Science and Engineering*, 2020.

[50] S. Khan, Y. Dewang, J. Raghuwanshi, and A. Shrivastava, “Nanoparticles as fuel additive for improving performance and reducing exhaust emissions of internal combustion engines,” *Int. J.*

Environ. Anal. Chem., vol. 00, no. 00, pp. 1–23, 2020.

[51] N. A. Usri, W. H. Azmi, R. Mamat, K. A. Hamid, and G. Najafi, *Thermal Conductivity Enhancement of Al 2 O 3 Nanofluid in Ethylene Glycol and Water Mixture*, vol. 79. Elsevier B.V., 2015.

[52] B. Gu, B. Hou, Z. Lu, Z. Wang, and S. Chen, "International Journal of Heat and Mass Transfer Thermal conductivity of nanofluids containing high aspect ratio fillers," *HEAT MASS Transf.*, vol. 64, pp. 108–114, 2013.

[53] R. Jadar, K. S. Shashishekar, and S. R. Manohara, "Performance Evaluation of Al-MWCNT based Automobile Radiator," *Mater. Today Proc.*, vol. 9, pp. 380–388, 2019.

[54] L. S. Sundar, M. K. Singh, and A. C. M. Sousa, "Turbulent heat transfer and friction factor of nanodiamond-nickel hybrid nanofluids flow in a tube : An experimental study," *Int. J. Heat Mass Transf.*, vol. 117, pp. 223–234, 2018.

[55] L. S. Sundar, M. K. Singh, and A. C. M. Sousa, "Heat transfer and friction factor of multi-walled carbon nanotubes – Fe 3 O 4 nanocomposite nanofluids flow in a tube with / without longitudinal strip inserts," *Int. J. Heat Mass Transf.*, vol. 100, pp. 691–703, 2016.

[56] K. Goudarzi and H. Jamali, "Heat transfer enhancement of Al 2 O 3 -EG nanofluid in a car radiator with wire coil inserts," *Appl. Therm. Eng.*, vol. 118, pp. 510–517, 2017.

[57] O. S. Ohunakin, D. S. Adelekan, T. O. Babarinde, R. O. Leramo, F. I. Abam, and C. D. Diarra, "Experimental investigation of TiO2, SiO2 and Al2O3 -lubricants for a domestic refrigerator system using LPG as working fluid," *Appl. Therm. Eng.*, vol. 127, no. 2017, pp. 1469–1477, 2017.

[58] O. S. Ohunakin *et al.*, "Performance of a hydrocarbon driven domestic refrigerator based on varying concentration of SiO 2 nano-lubricant Performance d ' un réfrigérateur domestique fonctionnant aux hydrocarbures , basé sur une concentration variable de nano lubrifiant SiO2," *Int. J. Refrig.*, vol. 94, pp. 59–70, 2018.

[59] J. Gill, J. Singh, O. S. Ohunakin, and D. S. Adelekan, "Energy analysis of a domestic refrigerator system with ANN using LPG / TiO 2 – lubricant as replacement for R134a," *J. Therm. Anal. Calorim.*, vol. 135, no. 1, pp. 475–488, 2019.

[60] M. Amiri, S. Movahedirad, and F. Manteghi, "Thermal conductivity of water and ethylene glycol nanofluids containing new modified surface SiO 2 -Cu nanoparticles : Experimental and modeling," *Appl. Therm. Eng.*, vol. 108, pp. 48–53, 2016.

[61] J. Gill, J. Singh, O. S. Ohunakin, and D. S. Adelekan, "Energetic and exergetic analysis of a domestic refrigerator system with LPG as a replacement for R134a refrigerant , using POE lubricant and mineral oil based TiO 2 - , SiO 2 - and Al 2 O 3 -lubricants Analyse énergétique et exergétique d ' un réfrigérateur domestique fonctionnant avec du GPL en remplacement du R134a , utilisant du lubrifiant POE et des lubrifiants à base d ' huiles minérales TiO 2 , SiO 2 et Al 2 O 3 .," *Int. J. Refrig.*, vol. 91, pp. 122–135, 2018.

[62] D. S. Adelekan *et al.*, "Case Studies in Thermal Engineering Experimental performance of LPG refrigerant charges with varied concentration of TiO 2 nano-lubricants in a domestic refrigerator," *Case Stud. Therm. Eng.*, vol. 9, no. October 2016, pp. 55–61, 2017.