



A systematic review on graphene-based nanofluids application in renewable energy systems: Preparation, characterization, and thermophysical properties

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ABSTRACT

Graphene has attracted much attention from various researchers because of its enhanced mechanical, thermal, and physio-chemical properties. Graphene exhibits high thermal conductivity and stability, less erosion and corrosion than other available nanoparticles. Various existing literature signifies a large portion of the research focuses on stability, heat transfer characteristics and thermal conductivity of Graphene nanofluids. This review article represents a detailed analysis of the preparation techniques, characterization methods stability evaluation, and thermal properties enhancements of Graphene nanofluids. Comparative analysis of the effects of nanoparticle size, volume concentration and temperature on thermal conductivity and viscosity of Graphene nanofluids are reviewed based on heat transfer application. Graphene nanoparticles significantly enhances the thermal conductivity, viscosity, and heat transfer capacity of base fluid. It is noticed that the thermal conductivity of Graphene nanofluids increases with an increase in temperature and volume concentration. Applications of Graphene based nano coolant in automotive radiator, electronic cooling, solar cells and fuel cells are presented. This article can be the rapid reference model with investigational and theoretical analysis for highly critical considerations that impact the thermal performance of graphene based nanofluids in different heat transfer trends. This review also outlined the imminent challenges and future scope of research in Graphene.

Introduction

The cooling system is being considered as heart of heat engine since it decides the overall performance of heat engine. Therefore, research is underway to deploy an efficient cooling system to enhance the performance of engine. Major purpose of this system is to throw away the generated huge amount of heat during operation and thereby improving the engine efficiency [1–3]. Generally, fins in radiators are used as per conventional cooling approach to enhance the cooling capacity of engine. These fins provided improved heat transfer and better heat transfer coefficient. Irrespective of improved cooling capacity, the fundamental approach of using fins has become extinct due to an increase in the size

of the radiator [4]. The radiator is an essential element in any engine system as it is the fundamental component of the cooling system. The efficiency of an automobile engine is measured not just on the performance of the engine but also dependent on high fuel economy and low emission [5]. Decreasing automobile mass through modifying the radiator design and radiator dimensions is certainly essential to enhance the performance of an engine [6]. Radiator performance can also be accelerated by using fluids which have good thermal characteristics [7] Nanofluid is a composition of primary fluids and nanoparticles of metals and its oxides. Nanofluids act as an efficient coolant when mixed with base fluids for example ethylene glycol to increase the capacity of heat transfer in the radiator by an approximate value between 15 and 40%. The thermal conductivity of GO and Water–Ethylene Glycol (60:40)

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Nomenclature			
nm	Nanometer	GNP	Graphene Nanoplatelets/particles
G	Graphene	HT	Heat Transfer
GO	Graphene Oxide	PVA	Polyvinyl Alcohol
GON	Graphene Oxide Nanosheet	CRGO	Controlled Reduced Graphene Oxide
CHF	Critical Heat Flux	H ₂ O	Water
NF	NanoFluid	CuO	Copper Oxide
SW	Surface Wettability	Al ₂ O ₃	Aluminum Oxide
C	Capillarity	SANSS	Submerged Arc Nanoparticles Synthesis System
IGO	Improved Graphene Oxide	CuSO ₄	Copper Sulphate
W	Water	HLB	Hydrophilic/Lipophilic Balance
DI W	De-ionized Water	pH	Measure of hydrogen
HM	Hummer method	EC	Electrical Conductivity
SDS	Sodium Dodecyl Sulfate	SiO ₂	Silicon Dioxide
SDBS	Sodium Dodecyl Benzene Sulfonate	D	Diffusion constant
TC	Thermal Conductivity (W m ⁻¹ k ⁻¹)	KB	Boltzmann constant
PHP	Pyroolidinohexiophenone	T	Temperature (°C)
D	Diameter	w _{bf}	Weight of base fluid
EG	Ethylene Glycol	ρ _{bf}	Density of base fluid (g/cm ³)
DW	Distilled Water	μ	Dynamic viscosity (kg/ms)
		φ	Volumetric concentration (%)
		ρ _{np}	Density of Nanoparticle (g/cm ³)

nanofluids was studied for different solid volume fractions up to 3% with temperature between 20 and 50 °C and study concluded nanofluid thermal conductivity increases by rise in temperature in all considered solid volume fractions [8].

Various published literature data confirms that heat transfer system can be enhanced by modified nanofluids utilized by nanoparticles such as Al₂O₃, CuO, and Graphene as an active working fluid [9]. Graphene, as a Nanofluid, is used intensively as a cooling element [10]. Graphene nanoparticles have gained huge popularity because of its high thermal conductivity value when related to carbon nanotubes, oxide ceramics (Al₂O₃ and CuO) and copper nanoparticles and robustness in thermal applications such as in photovoltaic system and heat transfer applications [11]. Graphene has a hexagonal structure which is similar to a honey-comb with largely dense carbon atoms [12,13]. This pattern is identical to the structure of various nanostructured materials, such as fullerene and carbon nanotubes [14]. Graphene Nanoparticles can be synthesized by various techniques such as Graphene derived from graphite, and Graphene derived from other sources such as epitaxial and CVD growth methods. These methods include Mechanical cleavage exfoliation, liquid -phase mechanical exfoliation, chemical cleavage exfoliation (graphite oxide, graphite intercalation compounds and graphite fluoride), Graphene produced from non-graphitic sources, chemical vapor deposition methods and Bottom-up synthesis methods [15]. Graphene Oxide (GO) and reduced GO are widely used as coolants because of their proven efficiency in large scale applications compared to Graphene. GO is an oxidized form of Graphene, which is two-dimension in nature [16]. The chemical structure of GO is large, and irregular compared to Graphene (Within 0.6 – 1.1 nm range), the range also depends on the preparation technique of GO. If the O-type groups are detached from a Graphene Oxide layer, then physical properties of GO will be like that of Graphene wherein GO exhibits properties of a semi-metal. Graphene is hydrophobic, and due to this nature, GO can be suspended easily into the base fluids. According to previous literature works [17,18], Graphene enhances thermal conductivity in nanofluids due to its excellent heat flow characteristics compared to conventional carbon-nanotubes [19,20].

In recent research, traditional techniques for heat transfer are replaced by using advanced fluids such as nanofluids [21-23]. With the advancements by using nanofluids as coolant, there were many sections of research carried out with different materials and base fluids for example ethylene glycol, water, and lubricant oil, coolants in radiators

and their performance were evaluated. Nanofluids in heat transfer systems enhances the efficient heat transfer coefficient and also modifies dimensions of the steam exchangers [24]. There is an insignificant measure of research done on nanofluids with various kinds of nanoparticles dispersed equally in an essential liquid, and these liquids are called hybrid nanofluids. Many technological advancements have evaluated the performance of different heat exchangers with nanofluids as the base fluid and have presented the improved result compared with conventional fluids [25].

Application of the hybrid nanofluids for effective transfer of heat in radiators is discussed by Bharadwaj, Mogeraya [26] and this research uses carboxyl Graphene and GO nanoparticles for determining the effectiveness of hybrid nanofluids. Obtained results display a substantial increase in the effectiveness of hybrid nanofluids by 10% with (3% CG & 3% GO). Graphene nanoparticles are gaining significance because of distinctive electrical, thermal and mechanical attributes. The good thermal conductivity in Graphene nanoparticles is an important constituent in improving the process of heat transfer between mediums [27]. The properties of Graphene nanoparticles on the performance of a diesel engine was determined by El-Seesy, Hassan [28], GNP was mixed with jatropha methyl ester fuel, and the performance of the diesel engine and its combustion characteristics was evaluated and better heat conductivity was demonstrated by using Graphene as nanofluid. Experimental analysis for investigating the thermal properties of GO nanofluid was presented by Nazari, Ghasempour [29]. In the study GO nanofluid was considered as active fluid for pulsating heat pipes. GO was mixed with water (0.25, 0.5, 1, and 1.5 g/lit) as base fluid. Results indicated that the addition of GO improved based fluid thermal conductivity and thermal resistance of pulsating heat pipe reduced by about 42%. The concept of utilizing a Graphene-based Nanofluids is influenced by the purpose of improving the mechanism of heat transfer by reciprocating between the advantages and disadvantages of any individual system [30].

Graphene nanoparticles

Nanoparticles are defined as a set of substances of which at least one dimension of it is less than approximately 100 nm. A nanometer is one-millionth of a millimeter roughly around 100,000 times smaller than the diameter of a human hair [31,32]. Two types approaches are used in nanofabrication, they are Top-down and Bottom-up methods [15]. The

Bottom-up synthesis method indicates that the nanostructures are synthesized against the substrate by piling atoms on one another, which provides growth to crystal planes, crystal planes are again stacked upon one another, resulting in the synthesis of the nanostructures [33-35]. A bottom-up method can be regarded as a synthesis approach where the building blocks are added to the substrate to form the complex nanostructures. Top-down synthesis method states to carving or cutting of bulk material to get a Nano-sized particle with the appropriate properties [36]. The bottom-up method is further beneficial than the top-down method because it has a good opportunity of producing nanostructures with fewer defects and further consistent chemical alignment and improved short- and long-range organization. The scientists and the researchers expect that nanoparticles will deliver the tradition of improving performance in a wide variety of products like electronics, displays, paints, batteries, micro-machined silicon sensors and catalysts [34,35,37].

Graphene forms can be explained with structures as shown in Fig. 1 a) 0D Zero dimensional structures [38] e.g. Nano pores and nanoparticles. b) 1D-system limited in one dimension such as laminated structures. c) 2D-system limited in two dimensions such as filamentary structures where the length is considerably larger than the cross-sectional dimensions. d) 3D-system limited to three dimensions such as typically composed structures of consolidated equiaxed crystallites.

Nanoparticles of the Graphene have significant benefits in comparison with other nanoparticles because of its high thermal conductivity, good stability, large surface area with less corrosion, erosion and consumes minimal pumping power [40-42].

The graph in Fig. 2 shows the published articles in various journals on nanofluids category in the last decade and indicates the growth of the Nanofluids increased with each year. Graphene has a very strong interest in science community in the last decade. Fig. 2 (b) shows the published articles on Graphene each year. Thermal Conductivity of Graphene is very high than the thermal conductivity of Diamond, Silver, Ag, Al, Ethylene Glycol, and water kind of materials.

Characterization techniques

Characterization refer to the features such as structure, composition & various physical, electrical, and magnetic properties. Below are general characterization methods.

X-ray diffraction (XRD)

X-ray diffraction (XRD) is one of the non-destructive types that adopts analytical methods to provide appropriate analysis about various lattice structures of crystalline substances such as crystallographic structures and unit cell dimensions. XRD works on the principle of constructive interference of x-rays. The interaction in the XRD mechanism provides constructive interference as per Bragg's law ($n\lambda = 2d \sin\theta$) [43] which correlates the wavelength of the incident radiations to the diffraction angle and lattice spacing. The equation of Bragg's law confines the relation between the wavelength (λ) of electromagnetic radiation to the diffraction angle (θ) and the lattice spacing (d) in a crystalline sample by scanning the sample through the arrangement of 2θ angles [44]. Siburian, Sihotang [45] performed XRD for Graphene, Graphene Oxide and Graphene Nanosheets. Peak value of Graphite is identified at 26.5 and interplanar distance ($d = 3.72$ nm). It shows crystalline structure graphite. Peak value for Graphene Oxide is identified at 11.6 and at interplanar distance of ($d = 7.6$ nm) due to oxygen presence in the functional group. Peak value for Graphene nanosheets is observed at 26.4 and interplanar distance of ($d = 3.36$ nm). Due to chemical reduction of graphite to Graphene nanosheets, the Graphene nanosheets has crystal structure. The XRD pattern of graphite, Graphene Oxide and Graphene nanosheets are shown in below Fig. 3. Graphite shows a sharp and tight peak ($2\theta = 26.5^\circ$ and 23.88°) whereas the Graphene Oxide shows a wide diffraction peak ($2\theta = 11.6^\circ$). XRD patterns of synthesized products were discussed by Aziz, Halim [46] which explain non-uniform ($2\theta = 17.2^\circ$) and uniform crystal structure ($2\theta = 26.4^\circ$) of Graphene Oxide and Graphene.

Ban, Majid [47] identified the XRD pattern of Graphite and Graphene Oxide. Identified Graphite has peak values at 50.68° , 54.62° , 59.84° , 71.56° . This shows crystallinity of the graphite. Distinguishable peak of graphite is observed at 26.56° and it has an interplanar distance ($d = 0.334$ nm). Peak value for GO is observed at 10.24° and has interplanar distance ($d = 0.80$ nm). This is due to presence of oxygen in the GO functional group [48]. Graphite oxidation process is monitored by Wang, Yang [49] using XRD and noticed that intensity of the (002) diffraction line (d -space 3.4 \AA at 26.23° C) has weakened slowly and completely disappeared. At diffraction peak 11.8° (d -spacing of 0.749 nm) with oxidation process, the intensity is increased. With continuous chemical treatment, Graphite powders are fully oxidized after 120 h to graphite oxide. Diffraction line also disappeared after 48 h showing full oxidation has been completed.

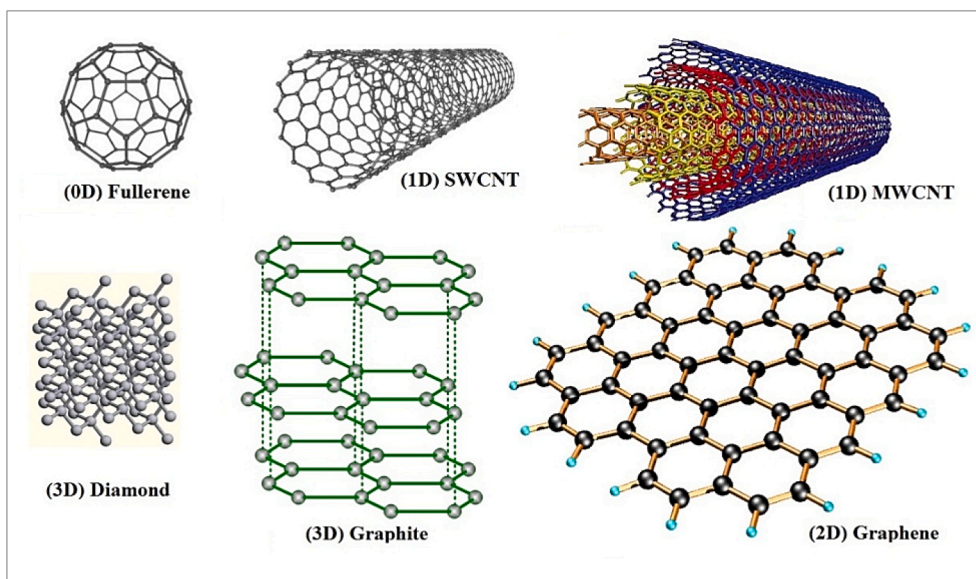


Fig. 1. Different forms of Nanomaterials, figure adapted from Atta, Galal [39].

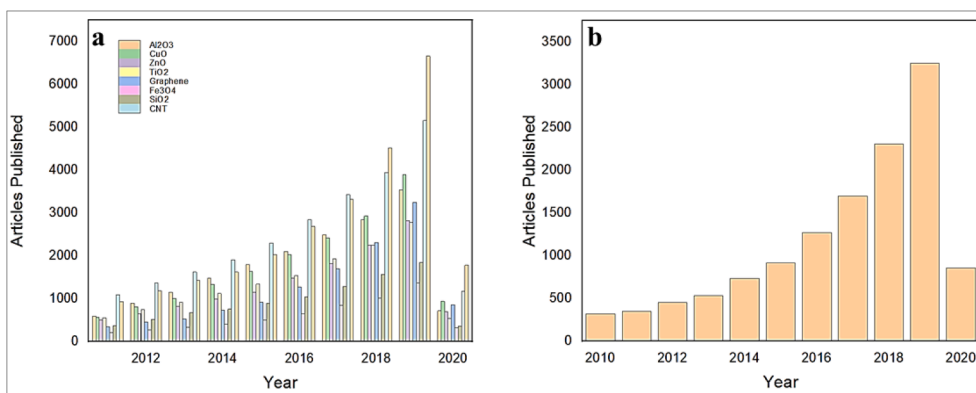


Fig. 2. (a): Various Nanofluid articles published (2010–2020), (b) Articles published on Graphene every year.

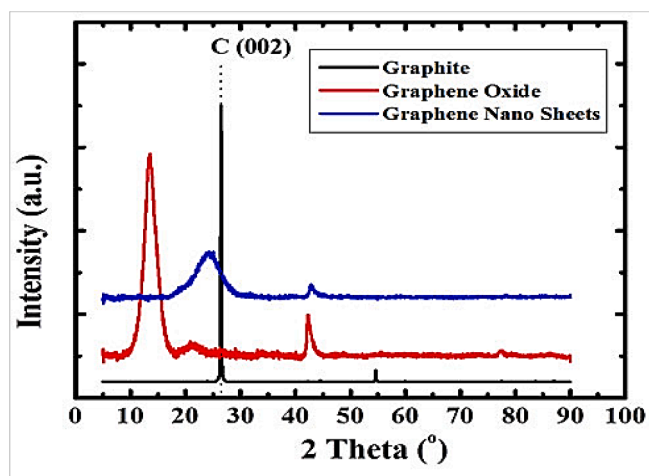


Fig. 3. XRD patterns of Graphite, Graphene Oxide & Graphene nanosheets, figure adapted from Siburian, Sihotang [45].

Scanning electron microscopy (SEM)

SEM is a prototype of an electron microscope which converts a sample into an image by scanning in a raster scan pattern using high-energy beam of electrons. The beam is associated with the atoms which constitute sample producing signals containing information related to the surface topography and composition of the sample. In space, electrons are formed via the source which is enhanced in a field gradient. The beam of electrons is passed through the electromagnetic lenses which focus on specimen. Due to this bombardment, there will be an emission of various electrons from the specimen and the image is displayed on the monitor [50].

Graphene Oxide fracture edge paper sample when imaged using SEM, showed that completely packed layers. The thickness was about 250 nm. Dikin, Stankovich [51] observed the SEM images of GO and rGO and identified that GO is layered and has hexagonal shape when compared to rGO, as it has material sheets very close to each other. The nanosheet edge thickness was less than 1 nm [52]. Selvam, Raja [53] has performed visualization of Graphene nanoplatelets layers in his research using SEM method and identified GNP are in form of layered structure. SEM image in Fig. 4 of Graphene taken by Ahammed, Asirvatham [54] at $7500\times$ magnification is less than 100 nm in thickness and is randomly dispersed as a flake-like structure.

Transmission electron microscope (TEM)

TEM constitutes of (i) few condenser lenses focusing on the electron

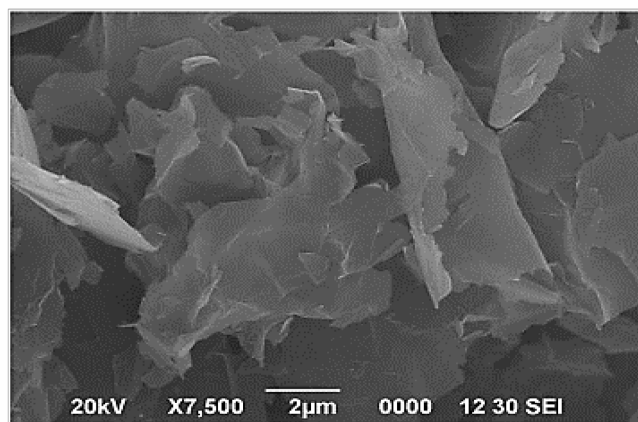


Fig. 4. SEM image of 0.15% vol conc. of Graphene by Ahammed, Asirvatham [54].

beam to observe the sample, (ii) a target focal point lens to form the diffraction in the back central plane and the picture of the sample in the image plane, (iii) some intermediate lenses to enlarge the image of the diffraction pattern on the monitor. If the thickness of the provided sample is less than 200 nm then the image produced is of low contrast and cannot be focused. To enhance the image contrast, an objective diaphragm is inserted in the back focal plane to select the transmitted beam and the crystalline form in Bragg orientation appears dark, samples which are in amorphous form appear bright [55]. TEM micrograph as shown in Fig. 5 give a view of sample having more than one layer and Graphene Oxide image (see image (a)) is not stable under high energy beam in contrast with the Graphene, which is stable and transparent under high energy electron. Graphene Oxide morphology in Fig. 5(a) shows irregular shape with un crumbled and non-uniform particle size with thick flat flakes. Un wrinkled structure indicates the non-removal of oxygen during oxidation process. The Fig. 5(b) indicates thin film morphology with wrinkled flake structure, the exfoliation process and sonication cause rapid removal of oxygen and functional groups from the layers.

Meanwhile SEM visualization of Graphene Nano platelets is used by Yarmand, Gharehkhani [56] and Selvam, Balaji [57] collected the TEM images and found uniformity of Ag nanoparticles & wrinkly surface and bending at the ends of GNP sheets. Xuan and Li [58] reported that TEM photographs of the suspended nanoparticles showed that the particles are dispersed in deionized water and some clustering occurred.

Zeta potential analysis

In this technique, the potential of a nanofluid is calculated using

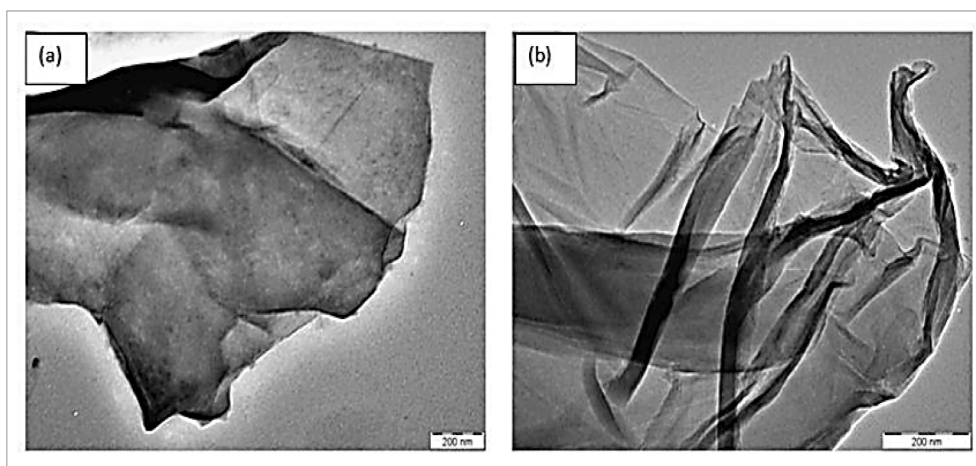


Fig. 5. TEM images of (a) Graphene Oxide and (b) Graphene by Aziz, Halim [46].

electric potential. The electric potential is the variance among the stagnant fluid layer (fixed with the dispersed particle) and the medium of particle dispersion [6,59]. The significance of zeta potential is the value obtained after analysis can be associated with colloidal dispersion stability. It means that the colloids are assumed to be electrically stabilized if they possess a high value of zeta potential whereas, the colloids which have less zeta potential will clot [60]. Zeta potential measurement range is between -200 to 200 mV considering a fluid with 15 mV potential difference is taken as a random value. This value is considered as reference value which distinguishes low-charged and high-charged surfaces. The colloids which range between 30 and 45 mV zeta potential is more stable, and the colloids which exceed 45 mV are assumed to have superior stability. The GO sheets structure in Fig. 6 states stable dispersions in the pH scope of $4-11.5$; the maximum value attained at pH 10.3 is -54.3 mV. The stable dispersions for r-GO sheets are formed at pH range $8-11.5$; the maximum value of zeta potential (ζ) is -44.2 mV at pH 10 . The identified rise in zeta potential is above pH 10.5 due to compression at high ionic strength.

UV/Vis spectrometer

UV-vis measurements are rapid, straight forward, easy and exact, and can have many successful applications in research and industry. It was demonstrated that a solid direct relationship existed between polymer fixation and specimen absorbance in clear unadulterated water, and polymer focus could be resolved utilizing an alignment bend. Ultraviolet-visible spectroscopy is viewed as a significant apparatus in analytical chemistry and science. It is one of the most regularly utilized

procedures in clinical chemical compound research facilities. This tool is utilized for the subjective analysis (qualitative) and recognizable proof of synthetics. The dispersion attributes of GO and EG + DW (Graphene Oxide, Ethylene Glycol and Distilled Water) suspension is evaluated employing fundamental sedimentation technique [62]. It is considered that the dispersion rate in nanomaterials has deterministic absorption bands of wavelength in the range of $200-600$ nm. Nanofluid stability is investigated through Thermal conductivity and UV Visible technique. NF is very stable, Thermal conductivity value enhanced with the increase in temperature. The long-term stability test conducted by Selvam, Lal [63] using UV-vis absorption (quantitatively) identified comparative conc. of Graphene NP/H₂O-EG nanofluids slightly reduces for a duration of two weeks. From below Fig. 7 of absorbance vs wavelength graph, the maximum peak for Graphene Oxide is at wavelength 230 nm with 0.354% of absorbance and the minimum peak value is at 300.5 nm wavelength with an absorbance of 0.242% . The maximum peak is obtained by Graphene Oxide when compared with Graphene (266.5 nm with 0.329% absorbance) according to Wazir and Kundi [64]

Fourier transform infrared spectroscopy (FT-IR) analysis

The FT-IR analysis is a characterization method which is utilized to get an infrared spectrum of absorption or emission of a solid, liquid or gas. High-spectral resolution data is collected by FTIR spectrometer for wide spectral range. The material will be scanned in all angles and refracted beam value of Graphene Oxide is between 600 and 4000 cm^{-1} . FTIR characterization will be performed using FTIR spectrometer. Below

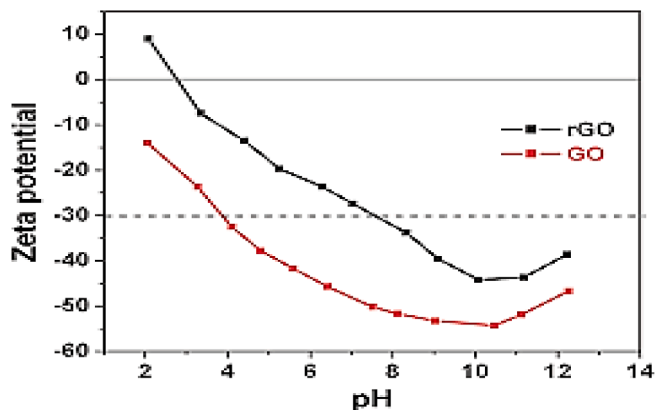


Fig. 6. Zeta Potential for Graphene Oxide (GO) and reduced GO [61].

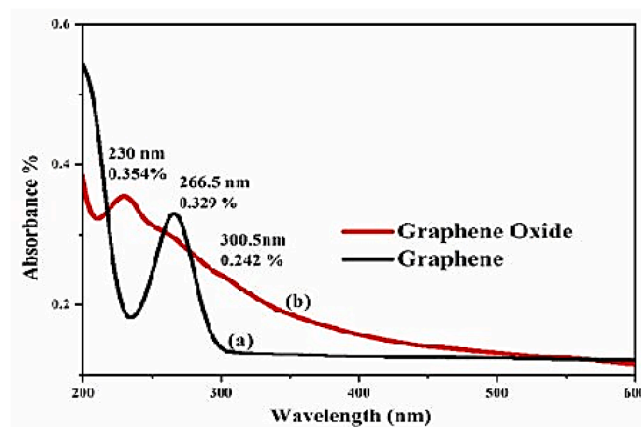


Fig. 7. UV-Vis absorption spectra of Graphene Oxide and reduced Graphene in DI Water [64].

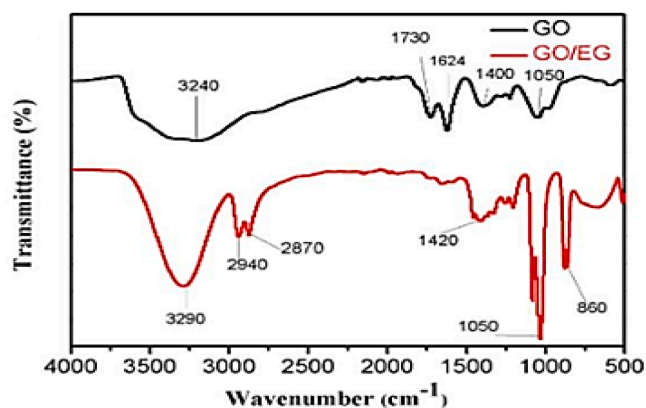


Fig. 8. FTIR analysis of Graphene Oxide and Graphene Oxide/Ethylene Glycol [65].

Fig. 8 shows the FTIR analysis of Graphene Oxide and Graphene Oxide/Ethylene Glycol. [65] The image provided clear information of the O-H functional groups and chemical bonds. Detail infrared spectra values comparison shows that two peaks are found at curve B at 2940 cm^{-1} and 2870 cm^{-1} value [66] but it is not shown at curve A. This is because of the vibrational stretching of C-H in ethylene glycol. As the carboxyl groups on surface of Graphene Oxide are substituted [67], the peak points on the curve B are reduced dramatically at 1730 cm^{-1} and 1624 cm^{-1} . We can conclude from this analysis that ethylene glycol is attached to the surface of Graphene Oxide at the spectra.

Thermogravimetric analysis (TGA)

Thermogravimetric analysis (TGA) is technique which is used for material characterization. A materials thermal stability is calculated. The weight fraction changes are calculated in temperature form at constant rate. The analysis is performed by slowly increasing temperature of the sample in heater and measured sample weight on analytical balance. Below Fig. 9 shows the TGA of GO and GO/EG by Zhang, Huang [65]. By comparative analysis of two curves Graphene Oxide and Graphene Oxide/Ethylene glycol, noticed that at three points mass loss processes. In the Graphene Oxide curve, weight reduction happened under $105\text{ }^{\circ}\text{C}$, which compares to 14.6% of the absolute mass and relates to the moisture evaporation contained in samples of Graphene Oxide. It has been noticed that temperature between $105\text{ }^{\circ}\text{C}$ and $240\text{ }^{\circ}\text{C}$, 26.6% weight loss has occurred because of the disintegration of oxygen-containing bonds on the Graphene Oxide surface. At the final stage between temperature $240\text{ }^{\circ}\text{C}$ and $800\text{ }^{\circ}\text{C}$, the mass loss is caused due to

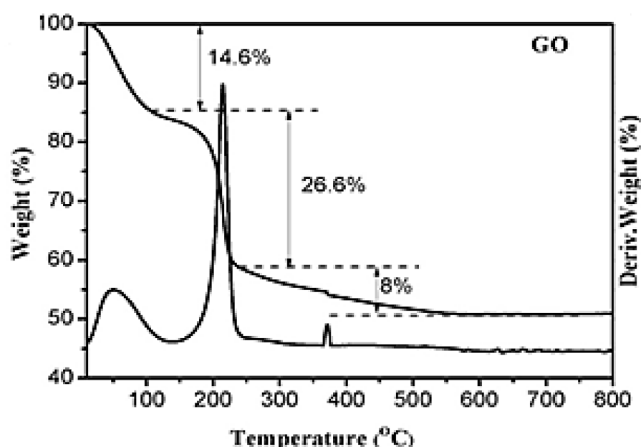


Fig. 9. TGA curve of GO and GO/EG [65].

sublimation of carbon skeleton, bringing about 8% loss of the absolute initial weight.

The main phase of GO/EG weight reduction additionally happens under $105\text{ }^{\circ}\text{C}$, however the weight reduction is just 4.8% of the entire mass. The subsequent stage happens between $105\text{ }^{\circ}\text{C}$ and $240\text{ }^{\circ}\text{C}$. In this stage, 15.7% of weight loss is occurred, because of decomposition of functional groups. The 18.4% weight reduction happens between $240\text{ }^{\circ}\text{C}$ and $800\text{ }^{\circ}\text{C}$, because of the sublimation of the carbon skeleton. By analyzing both GO and GO/EG curves, we can conclude that Graphene Oxide/Ethylene Glycol has much better thermal stability. It is proved by the higher decomposition temperature of carboxyl, hydroxyl & epoxy groups. Hence, we can presume that Ethylene Glycol is attached successfully on the surface of Graphene Oxide. The below Table 1 provides the detailed analysis of different concentrations of Graphene nanoparticles in fluids with important findings related to the characterization techniques.

Preparation techniques of the nanofluids

The schematic representation of preparing graphene based nanofluids is shown in flowchart Fig. 10. Basically, there are two types of preparation techniques for Graphene-based nanofluids: (a) One-Step preparation technique (b) Two-step preparation technique

One step method

Nanofluid is prepared by scattering of nanoparticles in base fluids which involves the deposition of different types of liquids and vapor chemicals [86-90]. The one-step technique is usually adopted to improve the stability of the nanoparticles and for reducing degree of agglomeration in nanoparticles. Evenly distributed nanoparticles are developed with a purpose to enhance substantial suspension in the base fluids and to decrease the manufacturing cost. Some propelled strategies were presented to develop the nanofluid using the one-step technique because of the trouble of constituting a stable nanofluid using the two-step analysis technique [91]. Fig. 11 represents the pictorial representation of one step nanofluid preparation. Several methods such as direct condensation, labor excision, evaporation and submerged-arc nanoparticle synthesis system (SANSS) are implemented in the process of developing the nanofluids using a one-step analysis wherein the metals are subjected to vaporization [92]. The metals are cooled using an appropriate mechanical technique to get the proper nanofluid. The physical techniques such as condensation and SANSS influences the dimensions of particles to increase the stability of nanofluid. SANSS is another proficient strategy to develop nanofluids employing various dielectric liquids [93].

Using dielectric liquids with different attributes of thermal conductivity, various frameworks of nanoparticles such as square-shaped, polygonal and circular shapes are procured, and different types of unwanted particle accumulation are eliminated [72]. Nevertheless, because of the incomplete chemical reaction and incomplete stabilization, outstanding reactants continue to stay within nanofluids, which remains the main drawback of this technique [60]. One-step analysis involving physical technology cannot handle extensive synthesizing of nanofluids, and also the production cost is high; hence two-step chemical analysis is gaining attention in recent times [94]. The one-step chemical technique is used in the preparation of Cu-nanofluids (Copper nanofluids) by decreasing CuSO_4 , sodium hydroxide and water in ethylene glycol using microwave irradiation. Evenly distributed copper nanofluids with proper stabilization were developed using one-step chemical reaction and nanofluids with mineral oil consisting of silver nanoparticles with reduced dimensions were also obtained by this technique [78]. The significant drawback of this procedure due to remainder of reactants were leftover and extra in the nanofluid because of fragmented response and stabilization which reduces the concentration of the nanofluid [95].

Table 1

The detailed summary of Nanoparticles, particle size, base fluids, preparation methods, characteristics techniques and findings of characterization.

NPs	Base Fluid	Particle size	Concentration (%)	Preparation Method	Characterization Technique	Findings	Reference
GNPs	W + EG	4 µm	0.1–0.5 wt%	Two-step	SEM, UV–vis, TEM, Zeta potential, DLS	The GNPs are sheet- shaped & represents a trimodal distribution with partial sedimentation and agglomeration.	Cabaleiro, Colla [68]
GNPs	EG	–	0.5,1,2,3,4 vol%	Two-step	XRD, FTIR, HRTEM, UV–vis, Raman spectroscopy	The GNPs assembled mesoporous materials were confirmed as plate-like shape and having hydroxyl functional groups bonded at edge with crystalline structure.	Lee and Rhee [69]
GO	EG, DW	t = 20 nm	0.001–0.006 wt%	Two-step	XRD, FESEM, TEM, FTIR, UV–vis, Zeta potential, Raman spectroscopy	The XRD pattern of Graphite Oxide(GtO) shows a strong peak at $2\theta = 11.68$ as well as FTIR spectrum of GtO confirms the successful oxidation of the graphite. The Raman spectra reveals G band of GtO shifts toward a higher wavenumber with respect to that of graphite.	Hadadian, Goharshadi [70]
G	EG	–	0.1, 0.125, 0.15 wt%	Two-step	XRD, TEM	CVD followed by XRD can be concluded that the obtained Graphene is pure. The Graphene shows the disordered structure like folded paper. Increased of hydroxide groups reveals a Graphene has best oxidation state.	Ghozatloo, Shariaty-Niasar [71]
GNS	EG	t = 0.7–1.3 nm	0.01–0.05 wt%	Two-step	TEM, AFM, FTIR	HRTEM image of the Graphene illustrated the interplanar distance was 0.43 nm. GNS with thin few-layer by AFM analysis confirm the thickness 0.7–1.3 nm. FT-IR and TG analysis explained the Graphene formed by reducing Graphene Oxide.	Yu, Xie [72]
GO, f-HEG	EG, DI-W	100 nm	0.02–0.08, 0.005, 0.009%	Two-step	FTIR, XRD, FESEM, UV–vis, Raman spectroscopy, TEM	The increase in the relative intensity of the disordered mode can be attributed to the increased number of structural defects and to the sp^3 hybridization of carbon for chemically induced disruption of the hexagonal carbon order after acid treatment.	Baby and Ramaprabhu [73]
GO	EG, DI-W	less than 100 nm	0.005, 0.007, 0.009, 0.02, 0.03, 0.05%	Two-step	UV–vis, FTIR, Raman spectroscopy, TEM, FESEM	UV comparison to TEG nanofluid, f-TEG nanofluid was homogeneous and was stable for long time. Raman spectra observation is that higher disorder in graphite leads to a broader G band, as well as to a broad D band of higher relative intensity.	Baby and Ramaprabhu [74]
GNS	EG, DI-W	–	0.008, 0.055, 0.083, 0.11, 0.138	Two-step	EDX, TEM, FTIR	Carboxylic acid and phenolic hydroxyl groups on the GO sheets are shown in SEM-EDX. The TEM image shows thin transparent sheet which is folded at the edges and the phononic properties are collected from Raman spectra.	Jyothirmayee Aravind and Ramaprabhu [75]
GNP	W	–	0.25–1.00%	Two-step	EDS, SEM, DSC	Sulfonic acid-functionalized Graphene exhibits a nanoplatelet-shape of wrinkled surfaces folding at the edges. The EDS spectrum shows C, O, S and Si presence due to impurities.	Agromayor, Cabaleiro [42]
GO, GNS	W	t = 5 nm	0.05–0.2 vol%	Two-step	DLS, TEM, UV–vis	The sheets are interconnected and entangled in TEM image and a trimodal distribution of Graphene sheet in DLS with 5 nm to 1500 nm long. Absorption spectrum measurements are taken from UV–vis	Sen Gupta, Manoj Siva [76]
HEG	EG, DI-W	20 nm	0.01–0.07%	Two-step	FTIR, FESEM, TEM, XRD	The crystallinity formation of the Graphene samples studied using X-ray diffraction (XRD), the curves of f-HEG show hydroxyl and carboxyl groups. The size of particle from the TEM image matches with Scherrer equation calculation using XRD.	Baby and Sundara [77]
GNS	DI W	500 nm	0.01–0.05 wt%	Two-step	TEM, Raman spectroscopy, SEM, FTIR	Wrinkles and folding's at the edge of Graphene sheets are identified and SEM image indicates the multi-layer, and few are in form of small agglomerates, Raman spectra shows the presence of carboxyl functional groups.	Ghozatloo, Shariaty-Niasar [78]
GO	DI W	1–3 µm	0.05, 0.1, 0.15, 0.2, 0.25 wt%	Two-step	XRD, UV–vis, SEM	XRD analysis shows one high-intensity broad peak about $2\theta = 12.5$ corresponding to (002) diffraction line (d-space 3.4 Å) plane of graphite the sizes of nanosheets varies in range of 1–3 µm. GO tend to congregate together to form multilayer agglomerates.	Hajjar, morad Rashidi [79]
GNP	DW	2 nm, d = 45 µm	0.025, 0.05, 0.07, 0.1 wt%	Two-step	XRD, UV–vis, Zeta potential, TEM, XPS	The specific surface area of GNPs shows a very effective influence on the stability of the nanofluid. The inclination is that the zeta potential values demonstrate an enhancement for higher specific surface areas of GNPs.	Mehrali, Sadeghinezhad [80]
GO	DI W	45 µm	0.01, 0.02, 0.04, 0.06 wt%	Two-step	Zeta potential, TEM, XRD, XPS, UV–vis	The zeta potential of all NDG nanofluids was negative and greater than -30 mV, which is in line with the excellent stability found by UV–Vis studies. The ultrasonication bath has a much less energy than the ultrasonication probe.	Mehrali, Sadeghinezhad [81]
GNP	DI W	less than 3.74, d=less than 3 µm	0.025, 0.05, 0.1 wt%	Two-step	FTIR, TEM	Acid treated GNP show carboxylic groups in FTIR and the surface deterioration is shown because of acid treatment in TEM analysis, and sonication caused wrinkling on the surface	Amiri, Sadri [82]
rGO	DI W	2 nm	0.05 wt%	Two-step			Zubir, Badarudin [83]

(continued on next page)

Table 1 (continued)

NPs	Base Fluid	Particle size	Concentration (%)	Preparation Method	Characterization Technique	Findings	Reference
GNP	DI W	-	0.0125, 0.025, 0.05, 0.075	Two-step	Raman spectroscopy, UV-vis, Zeta potential, XRD	A slight difference for different forms of Graphene are observed by TEM micrograph and XRD shows a different peak intensity for GO and rGO. The FTIR peak transition describes the disappearance of electron. GnP particles were mostly attributed to the electro-static and hydrophobic interaction between the particles. The unique mobilization of GnP strongly suggest the presence of GnP colloid in GO matrix.	Kazi, Badarudin [84]
GNP	DW	2 μm	0.1%	Two-step	Zeta potential, XRD, FTIR, FESEM, TEM FESEM, XRD, Raman spectra	The presence of defects and disorder formed in the sample are seen in D-band Raman intensity which caused by the acid treatment and silver coating. FESEM reveals the uniform silver coating on the Graphene sheets	Yarmand, Gharehkhani [56]
rGO	DI W	2 nm	0.05%	Two-step	Raman spectra, UV-vis, zeta potential, XRD,	Crumpled structure of rGO and confirmed reduction process is shown in TEM & UV-vis respectively. G and D band existence represent the scattering and defects in structure from the functional groups.	Zubir, Badarudin [85]

Two step method

An extensively utilized strategy to incorporate nanofluids is the two-step technique that incorporates nanotubes, droplets, nanoparticles, nanofibers, and nanosheets [6]. As shown in Fig. 12 in a two-step analysis, at first, the dry powder is obtained using chemical analysis such as sol-gel and vapor state and mechanical techniques like grinding and milling [86]. The finely grounded powder is then assorted with a base fluid for example ethylene glycol or SAE oil using ultrasonic vibrators, ball milling, amalgamation, and high-quality mixing. Frequent stirring decreases the aggregation of nanofluids which is a distinct concern in the synthetization of nanofluids. The methodology involved in a two-step analysis is a cost-effective way to develop nanofluids at an effective rate [93,96]. The nanofluids preparation in this method uses oxide nanoparticles to improve the stability of the nanoparticles. Because nanoparticles developed using oxide nanoparticles have high stability compared to metallic nanoparticles as the particles in dry powder get attracted easily to one another as of Van-der Waals force between the particles [78]. Significant methodology using surfactants is adopted in a two-step analysis to improve the stability in nanofluids. Though this technique is cost-effective, it faces significant concerns in transportation, drying, and storage. Clogging in nanoparticles reduces the thermal conductivity in nanofluids [80,97]. Many researchers are now using this modern technique of using Nanofluids as working fluids in the radiators instead of conventional base fluids [98]. This immensely helps in the increase and enhancement of the thermo-physical properties of the radiator. High Efficiency is obtained using this modern technique.

Hajjar, morad Rashidi [79] used the modified Hummers method and synthesized GO from graphite powder. The hydrophilic surface brought similarity between water and GO sheets. The GO sheets were properly suspended in the base liquid by only utilizing Ultrasonication. No dispersants are utilized. Wang, Han [99] stated that by using ionic fluid and without any added substances, a highly stable Graphene-based nanofluid can be prepared. Nanofluids with ionic fluids, as base liquid, are named ion nanofluids. Nanoparticle scattering in the base liquid was recognized using the optical photographs of liquid droimages displayed Graphene sheets even distribution in the fluid. Lee, Kim [100] GO sheets are suspended in water and synthesized Graphene Oxide water nanofluids. GO sheets are prepared using the CVD method. The obtained values of zeta potential and pH of GO nanofluid were -31.5 mV and 3.58, separately. It has been concluded that these values exhibit good stability by using two step method. Li, Zheng [101] introduced a methodology for setting up the solvent free Graphene nanofluid. Modified hummers method is used for preparing Graphene Oxide, the precipitate was prepared using ammonia solution in the sight of ionic surface modifier and sonication. Next step, they precipitate is washed to remove excess ionic surface modifier and dried it. Graphene chlorine salt with potassium sulfonate salt is mixed in methanol, and the then mixture has undergone dialysis treatment, further it is dissolved and centrifuged. Finally, the remaining particles were removed, and the supernatant fluid was gathered and dried for accomplishing the solvent free Graphene nanofluid.

Mehrali, Sadeghinezhad [81] formed nitrogen-doped Graphene from the Graphene Oxide using aqua thermal treatment with the help of ammonia. Using the two-step technique, the authors mixed the nitrogen-doped Graphene nanosheets in a base fluid. Using the NDG nanosheets in base fluid, the authors observed the electrical conductivity of the nanofluid increased. Ma, Yang [102] used functionalized Graphene sheets and prepared stable nanofluids. Functionalized Graphene sheets were readied through a two-step method with 3-glycid oxy propyl trimethoxy silane as the functionalization modifier. Graphene sheets are added to base fluid and prepared nanofluids. Yu, Xie [103] introduced a synthetic technique for nanofluid preparation with Graphene Oxide nanosheets. Graphene Oxide exfoliation in anhydrous ethanol resulted in nanofluid. Obtained nanoparticles was a free brown colored powder and scattered in Ethylene Glycol without surfactants. Martin-Gallego,

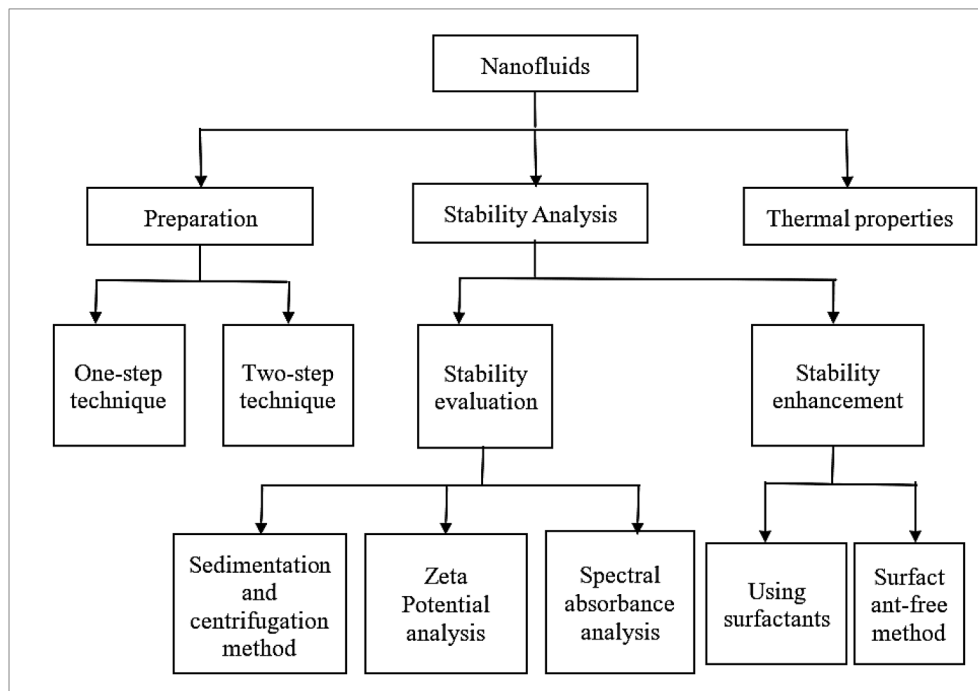


Fig. 10. Schematic representation of preparation methods, stability and thermal properties of nanofluids.

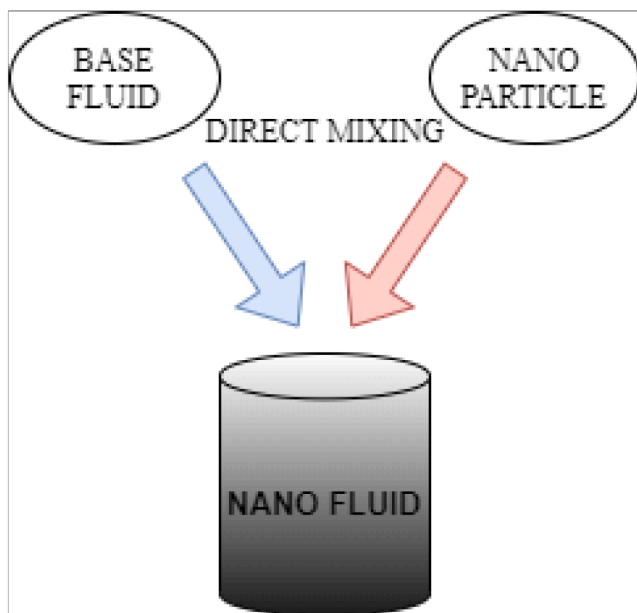


Fig. 11. Pictorial representation of One Step method.

Verdejo [104] synthesized Graphene Oxide at 1000 °C at inactive air condition. Carbon material with high surface area comprising of Graphene layers with remaining carbonyl, hydroxyl and epoxy gatherings are produced. Kole and Dey [105] utilized dried Graphene Oxide with hydrogen air at 200 °C to prepare hydrogen. Functionalization of HEG was finished by rewarding as integrated HEG with corrosive and Ultrasonication.

Stability evaluation and enhancement of graphene-based nanofluids

The nanoparticles agglomeration prompts the settlement and

obstruction of micro channels and reduces nanofluids thermal conductivity. In this way, the stability assessment is an important problem which impacts the properties of nanofluids implied for applications [95,106]. Indeed, even with advanced and innovative techniques to get ready nanofluids, many challenges still exist in preparing ideal nanofluid beyond focusing on improvement of agglomerates that sources the arrangement and stopping up small scale heat moving objects. The accumulation of nanoparticles in the liquids for the most part happens because of the solid Van der Waals power along with high surface territories between the Nano sized powder, and sedimentation [107,108].

Various stability evaluation methods, stability enhancement methods and stability mechanism are discussed in below section:

Nanofluids stability evaluation methods

Sedimentation method

The agglomeration process causes frequent clogging in nanoparticles due to which the thermal conductivity in nanofluids is decreased [109]. Hence, it is a significant concern to maintain the stability, it is essential in order to review and examine the factors affecting dispersion stability. The sedimentation technique is one of the efficient and straightforward methods to enhance nanofluid stability. The weight of the sediment of nanoparticles subjected to external pressure indicates the stability of the nanofluids [110]. Graphene-based nanofluids remain to be stable when the dimension of supernatant particles or their concentration is constant. A sedimentation balance technique is utilized to identify the nanoparticles stability in graphite, where sedimentation tray is immersed in the original graphite suspension [111].

Centrifugation method

Number of nanoparticles subjected to sedimentation was calculated for a predetermined time as it does not support observation for a longer duration. Hence, the centrifugation technique is implemented to determine the nanofluid stability using Graphene nanoparticles [20]. Singh and Raykar [87] applied centrifugation technique to assess the stability of Ag nanofluid obtained by AgNO₃ and using PVP stabilizer. Nanofluids are highly stable for 30 days and undergone 10 h centrifugation without sedimentation at 3000 rpm. This very high stability of silver nanofluids

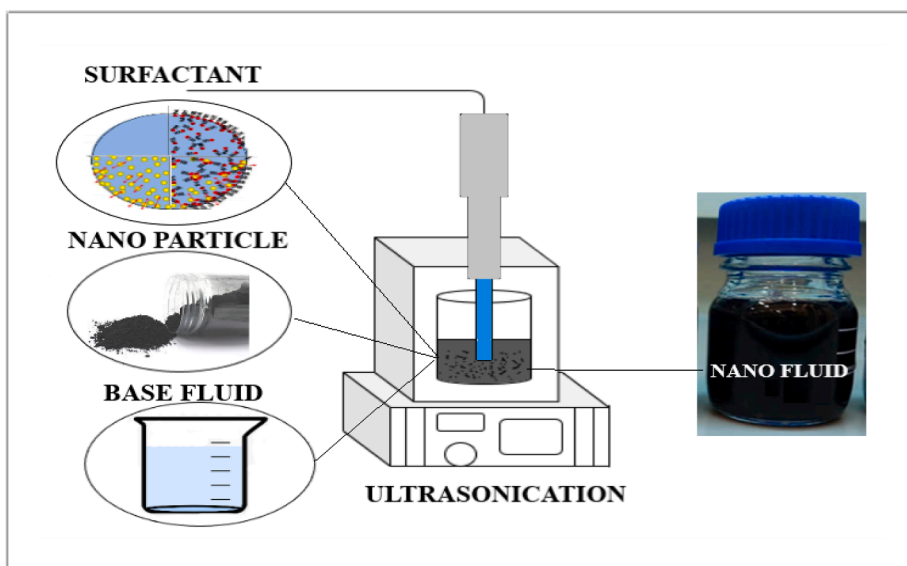


Fig. 12. Pictorial representation of Two-Step method.

was observed because of the defensive job of PVUsing the steric effect, PVP successfully decelerated the agglomeration of particles.

Zeta potential analysis

It is an electric potential in the interfacial twofold layer at the area of the slipping plane versus a point in the mass liquid away from the interface, and it shows the possible contrast between the scattering medium and the fixed layer of liquid joined to the scattered molecule. Zeta potential value can be used to identify the stability of colloidal scatterings. In this way, colloids with high zeta potential either positive/negative are stabilized electrically, while colloids with low zeta potential value tends to coagulate or flocculate. Zhu, Li [112] observed the stability of nanofluids at various pH value and SDBS concentrations.

From the above Table 2, related to various scholar’s research, the zeta potential is a consistent method for accurate colloidal dispersions stability. Stability of the particles dispersed in the fluids is defined by the

aggregation rate during collision. In general, the zeta potential values with 30 mV and above range concludes the stability, however for a clear aspect from the above table it is concluded that Graphene fluids with a zeta potential value of less than 35 mV is termed as moderate stability and above 45 mV of sustainable range is considered as good, and excellent stability range is above 50 mV. pH is also a significant parameter related with particle surface electrostatic charge and the farthest (IEP) [124] isoelectric point of pH where the particle carries zero electric charge. The value of pH can be changed by adding HCL/ NAOH solution into prepared fluid. The value of zeta potential increases as the pH value from the IEP changes and from all the literature the highest zeta potential value (>45 mV) is obtained at a 9–11 value of pH. The below Fig. 13 shows the zeta potential analysis way of representing stability.

Table 2

Detailed summary of Nanofluid, base fluid, Zeta Potential value, pH value and remarks of various authors.

Nanofluid	Base fluid	Zeta-potential value	pH value	Observation	Remarks	Reference
GNP	W + EG	- 30 to - 40 mV	~ 8.5	Stable after adding surfactant SDBS	Zeta value less than 30mv without surfactant	Sani, Vallejo [113]
GO	DI-W	-48.6 mV	10	Stable	Optimum range of pH is stated as between 7 and 11	Kashyap, Mishra [114]
GO	DW	-45.4 mV	10	Good stability	Strong repulsive forces resulted in high negative zeta value.	Hadadian, Goharshadi [70]
GO	W	-43.5 mV	8,10	Confirmed stability	Stability of colloidal dispersions are dependent on zeta potential high negative or positive value	Askari, Koolivand [115]
CRGO	DI-W	-50.9 mV	12	Good dispersion stability	With increase in temperature and volume concentration the stability increased	Zhang, Wang [116]
GO	W	-	8	Good stability	Stability remained same with increase in sonication time	Yang, Ji [117]
GO	EG + W	-40 to -43 mV	5	Stable	Because of repulsive charges, zeta value decreased as pH increased.	Cabaleiro, Colla [68]
rGO	W	-39.1 mV	7.5-8.5	Good stability	Ph decreased with increase in hours after preparation	Kamatchi, Venkatachalapathy [118]
GO	DW	-35 mV	7	Good dispersion with stability	As the value of pH increased to 8.24, value of zeta reached to -24mv	Park, Lee [119]
GO	W	-41 mV	9	Good stability	Functional groups attributed the stability in nanofluid with Graphene	Ranjbarzadeh, Isfahani [120]
GO	W	-31.5 mV	3.58	Moderate stability	Stability can be increased by adding the surfactants with small amounts.	Lee, Kim [100]
GO	DI-W	-40.1 mV	9-12	stable	Graphene itself showed the higher zeta value SDS surfactant given the max zeta value of -38.3 mV.	Cakmak [121]
G	W	-45 mV	-	Good stability	CMC surfactant has been used to improve the uniform stability of nanoparticles	Kazemi, Sefid [122]
GO	W	-41 mV, -50 mV	>4	stable	Increased concentrations of Graphene resulted in higher zeta potential value.	Esfahani, Languri [123]

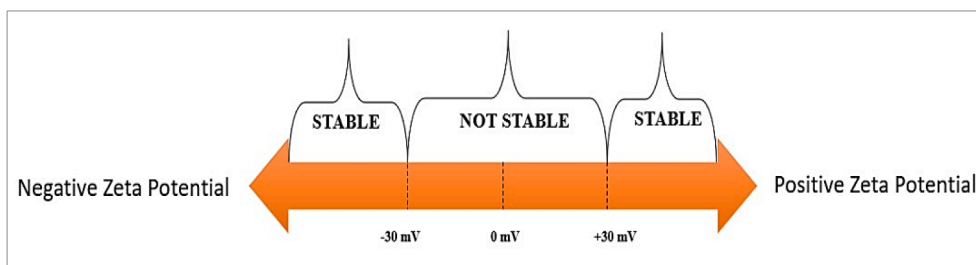


Fig. 13. Stable and unstable representation of Zeta potential.

UV-vis spectral analysis

In this method the stability of nanofluids is evaluated using UV-vis spectrometer. The results obtained in this method provides quantitative output with respect to various concentrations of nanofluids. Hwang, Lee [59] utilized this method to identify the relative stability of MWCNT at various concentrations and pH. Surfactant addition to the nanofluids improved the nanofluid stability. If the characteristic absorption wavelength value is in between 200 and 1100 nm, the UV-vis spectral analysis method is very simple and dependable to identify the stability of nanofluid.

Enhancing the stability of graphene nanofluids

Using surfactants

The surfactants, otherwise known as dispersants, are adopted to increase nanofluids stability. Accumulation of these dispersants in 2-phase model is an effective technique to increase the nanofluid stability. In a 2-phase model, a dispersant identifies the interfacial state of the two-phases and forms continuity between fluids and nanoparticles [60]. The selection of an appropriate surfactant is a significant concern. It depends on the kind of base fluid used: in case of a polar solvent, water solvable dispersants are used; or else, oil solvable surfactants are selected. For non-ionic dispersants, solubility is evaluated using a hydrophilic/lipophilic balance (HLB) value. The surfactants are oil-soluble if the HLB number is less whereas they are water-soluble if they possess a higher HLB number [86]. Few of the important different types of surfactants used with Graphene nanofluids are presented in below Fig. 14.

Surfactants also plays an important role in effecting the

thermophysical properties of nanofluids. Mehrali, Sadeghinezhad [81] Used Triton X- 100 as surfactant. It is used because of its benzene ring structure molecules in it can disperse the NDG easily by forming a shell around the surface. Triton X-100 has very less optimum amount value. The author concluded that nanofluids were stable for 6 months when used Triton X-100 as surfactant with 1hr ultrasonication. Haque, Kwon [125] used SDBS as surfactant for dispersing MWCNT as it is effective and SDS is helpful as surfactant for Graphene. Due to the chemical structure, different surfactants are used for both materials and stability has been observed. It has been concluded that Graphene – SDS with 20 min probe, nanofluid is stable for 4 days and efficient.

Wusiman, Jeong [126] experimentally found that SDBS is effective dispersant for MWCNTs for particular weight ratio. It lead in preparing a stable nanofluid when SDBS is dispersed in water. Sarsam, Amiri [127] experimentally investigated stability of GNP nanofluids samples at 0.1 wt% using four surfactants Gum Arabic, SDBS, SDS and CTAB. Identified that excessive foam is formed in nanofluids for all surfactants except Gum Arabic. Thermal conductivity value of GNP nanofluid increased and maximum stability value is achieved at 60 min probe time when SDBS surfactant (1–1) is dispersed in water-GNP.

Surface modification techniques: surfactant free method

Functionalized nanoparticles such as silica oxide (SiO₂), zinc oxide and Graphene nanoparticles represent a surfactant-free technique. These particles do not form any deposition coating on the heated exterior surface after the pool boiling process [72]. Though adopting dispersants is found to be a pronouncing technique to improve the nanoparticle dispersibility with primary fluids, it raises many concerns such as

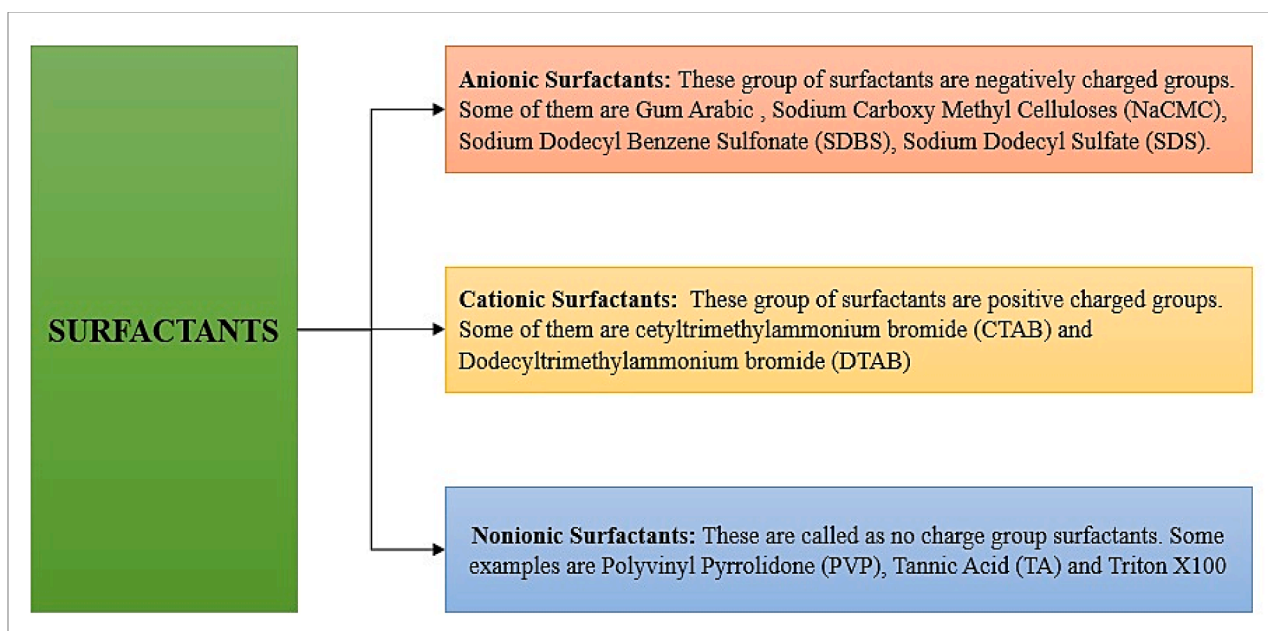


Fig. 14. Different types of surfactants used for Graphene based nanofluids.

problem in the process of heat transfer, foam formation in the heating process, introducing thermal resistivity between base fluid and nanoparticles and reduced reciprocity of surfactant molecules with an outer layer of nanoparticles [128]. These problems are addressed by selecting functionalized nanoparticles which improves the long-term stability and durability of nanofluids using a surfactant-free method.

Stability mechanism and equation

The rate of aggregation of nanoparticles dispersion in base fluid is defined as stability mechanism [129]. Usually defined by number of collisions and cohesions during the collision. Nanoparticles begin to adhere together to form structure at bigger scope and size that may cause sedimentation and agglomeration [130]. Each nanoparticle stability is identified by the sum of Van der Waals attractive forces and the electrical twofold layer repulsive forces happening between the nanoparticles when each of them approach together due to the Brownian movement. The sedimentation of prepared nanofluids after 15 days and 45 days is shown in Fig. 16 and observed that there is no sedimentation observed for 15 days and after 45 days agglomeration of particles was found indicating that the Graphene based nanofluids have good dispersion [116].

Thermo-physical properties

Volume fraction of the fluid

The Nanofluids can be prepared by calculating the quantity of nanoparticles for required volume concentrations using the following Eq. (1) [33].

$$\phi = \left[\frac{\frac{w}{\rho_p}}{\frac{w}{\rho_p} + \frac{w_{bf}}{\rho_{bf}}} \right] \times 100 \tag{1}$$

where, the volume concentration of nanofluids is ϕ (%), w is the mass and ρ stands for density. The subscripts p refers for nanoparticles and bf base fluid.

Density

The density plays a key influence which can affect the properties of heat transfer. Nevertheless, very few studies are available on the effect

of density. As the density of nanoparticles is higher compared to liquids, it directed in being certain that increase in nanofluid density with increase of vol. concentration of nanoparticles.

The effective density is the parameter of concentration of nanofluid [116,131]

$$\rho_{nf} = \phi\rho_s + (1 - \phi)\rho_f \tag{2}$$

Above equation embraces for various weight fractions with negligible differences. Some inquiries describe on the impact of temperature and vol. concentration on the density in water based nanoparticles and decided a prototype that can work for each other [132].

$$\rho_{eff} = 1001.064 + 2738.6191\phi_p - 0.2095 T; \text{ for } 0 \leq \phi_p \leq 0.4, 5 \leq (^\circ\text{C}) \leq 40,$$

ρ_{eff} signifies the nanofluid effective density, ϕ_p signifies vol. concentration where as T signifies temperature value.

Agromayor, Cabaleiro [42] calculated density values at different temperature ranges between 15 and 40 °C and plotted graph. It is concluded from the Fig. 15 that, with increase in Graphene nanoparticles concentration, density of nanofluid increased, the density of GNP nanofluids is calculated by Eq. (2).

The author Ijam, Saidur [62] has investigated effect of concentration

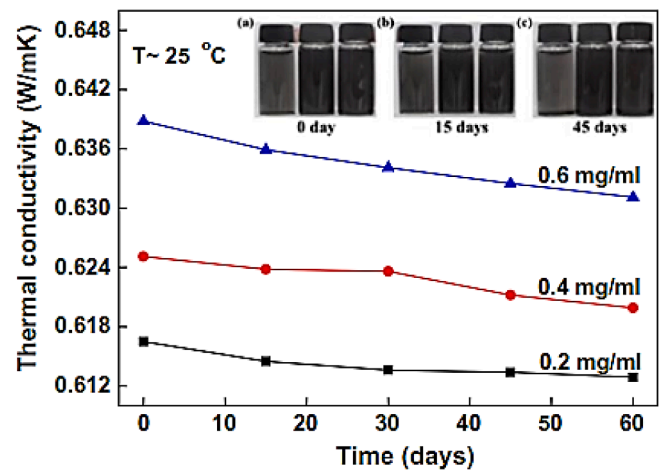


Fig. 16. Thermal conductivity of the CRGO/water nanofluids with (a) fresh prepared, (b) 15 days, and (c) 45 days [116].

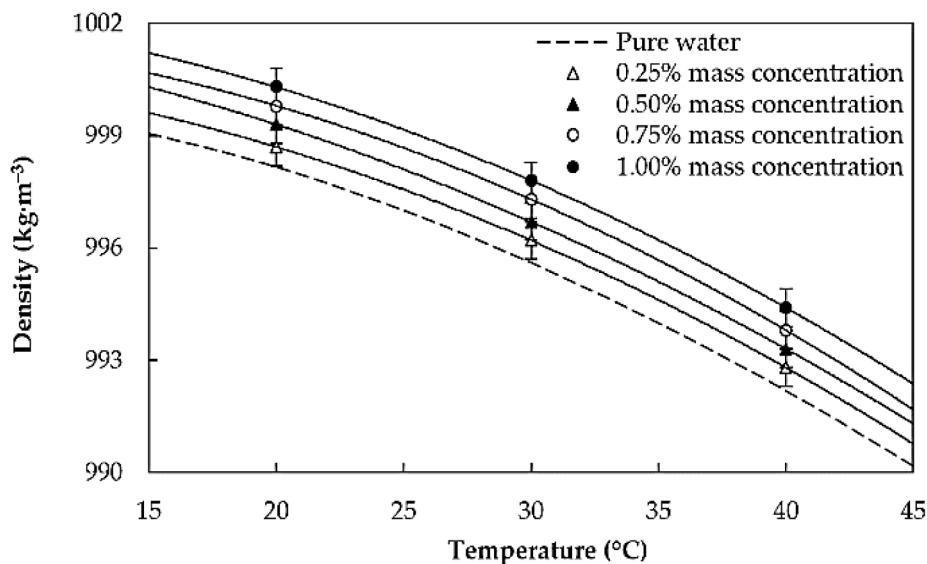


Fig. 15. Density of GNP nanofluid at various temperature Agromayor, Cabaleiro [42].

on density value of GONs-DW/EG nanofluid at various weight fractions and plotted graph. with the addition of GONs, the density of base fluid decreased. The results are compared with theoretical model developed by Pak and Cho [133] and confirmed that model is not able to predict density of nanofluid. The author also calculated effect of temperature on GONs-DW/EG density value at various temperature between 25 and 45 °C. It is concluded that with increase in temperature, the density of base fluid decreases and graph is plotted. Density is reduced by 1.134–1% between 25,30,35,40, and 45 °C at 0.00 wt%, 0.01 wt%, 0.05 wt%, 0.07 wt% and 0.10 wt%.

Thermal conductivity

Thermal conductivity of any material is described as the volume of a substance to transfer energy in the form of heat [134]. An analysis of convection heat transferring concept, Base fluid thermal conductivity plays an important role. Evolution of nanoparticles in various base substances such as mineral oil, lubrication oil, glycerol, ethylene glycol and methanol improve the thermal properties of nanofluids. Two critical factors influence thermal conductivity in nanofluids: Liquid layering and Brownian motion. In Brownian motion technique, nanoparticles collide with each other in base fluid, which enables direct transfer of heat between two particles which enhances the thermal conductivity of base fluids [111].

The Brownian motion is determined by the particle diffusion constant D , defined by Stokes-Einstein formula as shown in Eq. (3). The Brownian motion is characterized by the particle diffusion constant D

$$D = \frac{[KbT]}{3\pi\mu d} \quad (3)$$

where, K_B is Boltzmann constant, T is temperature, μ is viscosity

In various existing literature, it is represented as thermal conductivity is mainly reliant on temperature. Rise in temperature of nanofluids leads to decreased viscosity of base fluid and increase in Brownian motion among the nanoparticles which again increases the thermal conductivity (2.0 vol% and 5.0 vol%) for the temperature range from 10 °C to 60 °C. The dimension of nanoparticle and its thermal conductivity influences the concentration depending on the base fluid property. The properties of solid-liquid leaves a prominent impact on thermal conductivity (from 12.1% to 32.1% at 50 °C) of the base fluids [135].

Graphene manifests superior thermal conductivity compared to different carbon nanotubes. A non-equilibrium technique known as dynamic molecular technology was employed to study thermal properties of Graphene nanoribbons composed of a variety of edge shapes. The results obtained from this technique exhibited robust dependency on the length of the Graphene nanoparticles. With increasing concentration, Graphene and Graphene Oxide tends to exhibit improvement of thermal conductivity when compared with other fluids such as high-viscous fluids, ethylene glycol, water and oils [136]. They exhibit properties similar that of metallic nanofluids and metal-oxide nanofluids [25]. The increasing concentration in nanofluids due to Graphene nanoparticles leads to the aggregation of particles and assists in percolation, which helps in thermal conductivity improvement [137,138]. The base fluids thermal conductivity was prominently improved due to the dispersion of Graphene nanoparticles (Up to 86% for 5% dispersion of Graphene [72]). The heat transfer property of Graphene shows that the Graphene layer is an excellent filler to enhance the thermal conductivity of epoxy composites with 17.5% enhancement for Graphene [17]. Hamze, Berrada [139] stated, FLG concentration of 0.05, 0.10, 0.25, and 0.50 wt%, thermal conductivity of nanofluid increases by 4.2, 5.5, 12.2, and 23.9%, respectively, as compared to the corresponding base fluids when using Triton X-100 as a surfactant. The thermal conductivity enhancements are 1.3, 3.0, 9.9, and 18.3% for P-123, Pluronic. Finally, using Gum Arabic, thermal conductivity values increased by 2.1%, 4.0%, 10.5%, and 21.5%. From the Fig. 16 it is observed that the thermal

conductivity for Graphene nanofluid at 25 °C for 0,15 and 45 days. The thermal conductivity (0.638 W/m-k) is maximum at 0.6 mg/ml volume fraction of the nanofluid. For 0.4 mg/ml dispersion, 0.625 w/m-k was observed and for 0.2 mg/ml, 0.616 w/m-k was observed. After 15 days the thermal conductivity is reduced due to sedimentation of the nanoparticles for all three concentrations and continued to reduce for 45 days. Approximately 1 to 1.25% of thermal conductivity is reduced from 0 to 15 to 45 days. Apart from this the different factors affecting the thermal conductivity is shown in Fig. 17 and different equations by authors are represented in Table 3.

Specific heat

The specific heat of the nanofluid is a function of concentration and specific heat of base fluid [33].

$$C_{p,nf} = \frac{\phi(\rho C_p)_s + (1 - \phi)(\rho C_p)_f}{\rho_{nf}} \quad (8)$$

According to Ijam, Saidur [62] study explains that the specific heat increased about 3.59–5.28% for Graphene Oxide Nanosheets (GONs), DW and Ethylene Glycol nanofluid at 0.05% weight conc. and value reduced about 9.05 – 8.215% by 0.10% weight conc. for temperature scope of 20 to 60 °C. Shahrul, Mahbulul [144] through the comparative review on specific heat identified volume concentrations, temperature and various sorts, nanoparticle size including base liquids exhibit substantial impact on nanofluid specific heat. With Volume concentration increase, Specific heat value for the nanofluids decreases. Liu, Wang [145] in their study using Sapphire method (DSC,Q20,TA Instruments) for Graphene-dispersed nanofluids, it has been identified that the specific heat and density display a minimal reduction of about 3% and 2.8% respectively as compared with 1-hexyl-3-methylimidazolium tetrafluoroborate (HMIM)BF₄. Pak and Cho [133] investigated nanofluid specific heat and identified with increment of particles in water, the specific heat is decreased. As the temperature increased between 20 °C and 50 °C, the specific heat of samples increased [146]. Obtained specific heat value shows the specific heat of nanofluid is 2.25% higher than value at base fluid for temperature of 50 °C, 0.06 wt%. Hybrid nanofluids specific heat capacity increased with increase of Activated Carbon Graphene Composite (ACG).

Viscosity

Yang, Ji [117] experimentally measured the dynamic viscosity and thermal conductivity of the Graphene Oxide and Water/Ethylene Glycol nanofluid. Results showed with improved thermal conductivity along with 35% decrease of dynamic viscosity for 0.01 to 0.1% vol. conc. and 25 °C to 45 °C, mass fraction and temperature respectively. Sarsam, Amiri [127] conducted experiments with the water and Graphene obtained nanofluid in different concentrations. Results show with increase in the concentrations, it has enhanced viscosity. Viscosity is influential property in heat and flow applications of nanofluids. Park and Kim [147] probed the viscosity and observed the increment for Graphene & DW nanofluid with higher value (>1.2 times at 15 μm compared with 5 μm size) at volume fraction of 0.001–0.01%. The functionalized Graphene (f-HEG) viscosity was studied by Kole and Dey [105] using EG 70%/W 30% nanofluid at concentration 0.041 to 0.395% was recorded with 100% increment when compared to base fluid showing non-Newtonian behavior. The rise in the temperature decreases the viscosity and particles Brownian motion increases which results in thermal conductivity enhancement [148]. Hadadian, Goharshadi [70] studied the viscosity of Graphene Oxide and Ethylene Glycol nanofluid. Results obtained 81.29 cp, at temperature 20 °C and 0.005 mass fraction of GO nanosheets (below shear rate ~ 25 s⁻¹). Viscosity of nanofluids diminished non-linearly at expanding shear rate, showing solid shear diminishing conduct at low shear rates. Nanofluids viscosity diminished

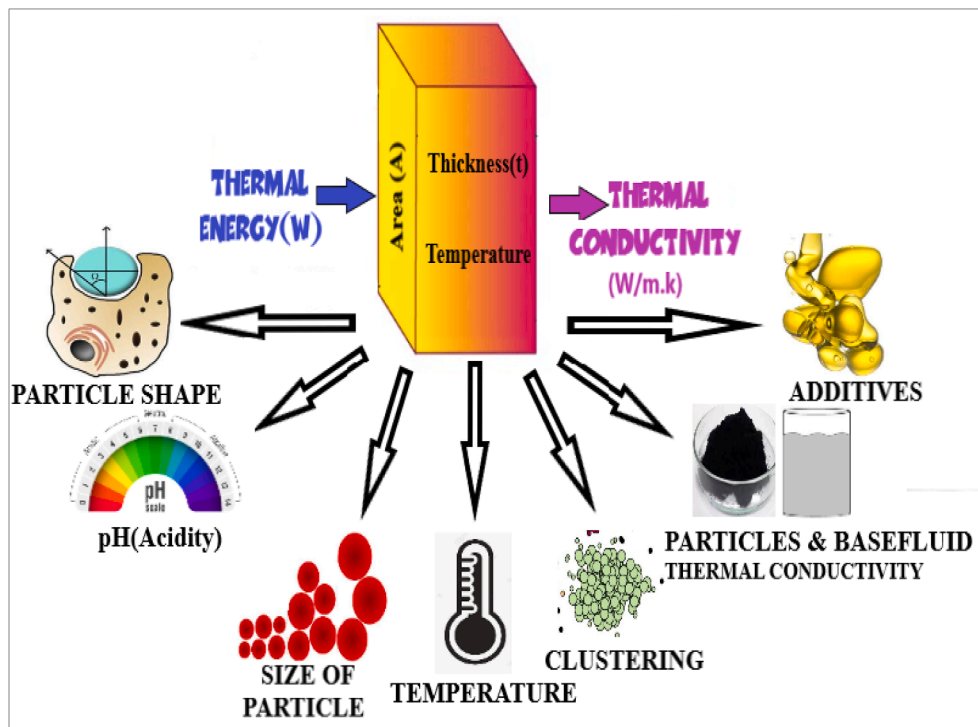


Fig. 17. Factors effecting the Thermal conductivity.

Table 3
Thermal conductivity formulas mentioned by different authors.

Reference	Formula	Important findings	Remarks	Eq. no
Maxwell [140]	$k_{eff} = \frac{k_{np} + 2k_{bf} + 2(k_p - k_b)\phi}{k_{np} + 2k_{bf} - (k_{np} - k_{bf})\phi} k_{bf}$	Thermal conductivity of the spherical particle, the base fluid, and the volume fraction of the solid particles.	Equation is used for solid or liquid state mixtures with large particle size and low solid concentrations	(4)
Hamilton and Crosser [141]	$k_{eff} = \frac{k_{np} + (n-1)k_{bf} - (n-1)(k_{bf} - k_{np})\psi}{k_{np} + (n-1)k_{bf} + (k_{bf} - k_{np})\psi} k_{bf}$ Where, $n = \frac{3}{\psi}$	This represents the boundary between the spherical particle and the base fluid, here n is the empirical shape factor given by $n = 3/\psi$, and ψ is the particle sphericity, known as the ratio of the surface area of a sphere with volume equal to that of the particle, to the surface area of the particle.	This equation is used for liquid or solid mixtures with non-spherical shape with ratio of conductivity of solid to liquid > 100.	(5)
Xue [142]	$9(1 - \frac{\phi}{\lambda}) \frac{k_{eff} - k_{bf}}{2k_{eff} + k_{bf}} + \frac{\phi}{\lambda} (\frac{k_{eff} - k_{c,x}}{k_{eff} + B_{2,x}(k_{c,x} - k_{eff})} + \frac{k_{eff} - k_{c,y}}{2k_{eff} + (1 - B_{2,x})(k_{c,y} - k_{eff})}) = 0$ $\lambda = \frac{(a+t)(b+t)(c+t)}{k_{np} + 2k_{bf} + 2(k_{np} - k_{bf})(1-\beta)^3 \phi}$	This model represents the interface among the base fluid and solid particles.	This model of effective k_e is on the theory of average polarization	(6)
Yu and Choi [143]	$k_{eff} = \frac{k_{np} + 2k_{bf} + 2(k_{np} - k_{bf})(1-\beta)^3 \phi}{k_{np} + 2k_{bf} - (k_{np} - k_{bf})(1+\beta)^3 \phi} k_{bf}$	This represents the nanoparticle size and thickness, $\beta = h/r$ nano-layer thickness ratio (less than 10 nm) to the original particle radius.	this is an improved model for Maxwell equation based on effective medium theory of solid nanoparticles	(7)

fundamentally with expanding temperature, while it expanded with increasing mass division.

Viscosity of nanofluid is dependent on various factors. Size of nanoparticle, volume concentration, shape of nanoparticle, shearing rate and time, agglomeration of nanoparticle, base fluid properties and layer of nanoparticle as well as shown in Fig. 18 Various investigational studies demonstrated that the accumulation of nanoparticles to conventional fluids which are good at heat transfer leads to an increase in the viscosity of liquid. With additional increment of nanoparticle concentration also provided with an increase of viscosity non-linearly. As temperature value increases, the nanofluid viscosity values decreases. The viscosity of nanofluids diminishes when expansion in temperature which is typically portrayed by [149] an exponential bend. This alluring to set up with nanoparticle size ≤ 100 nm, in light of the fact that a greater size in the micro regime prevents useful application because of

scraped area, the higher rate of settlement, the pressure drop in streamline and stopping up of hardware. Study indicated that nanoparticle size also an additional significant influence which impacts the nanofluids viscosity. Naturally, with the molecule size decreases, viscosity of suspension gradually increases [150-152]. Below Table 4 shows the different equations of viscosity mentioned by various authors.

According to Ijam, Saidur [62] the nanofluids demonstrated a shear diminishing conduct at lower shear rate; in any case, it carried on in Newtonian way with higher shear rate. The viscosity of GONs-DW/EG nanofluid is enhanced 35% at 0.10 wt%, contrasted with base liquid 20 °C temperature. It further increased by 48% between 20 and 60 °C temperature values at similar stacking of GONs. Esfahani, Languri [123] study explains that base fluid have high impact on rheological properties of nanofluids at moderately lesser fixation, however for nanofluids which are generally in high focus, collaboration amongst base liquid and

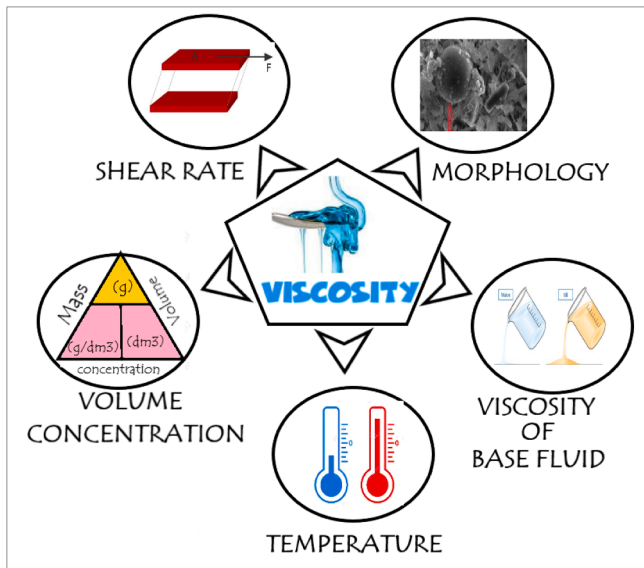


Fig. 18. Factors effecting the Viscosity of nanofluid.

Table 4
Viscosity equations by different authors.

References	Model equation for Viscosity	Equation
Einstein [154]	$\mu_{nf} = \mu_{bf}(1 + 2.5\phi)$	(9)
Wang, Xu [155]	$\mu_{nf} = \mu_{bf}(1 + 7.3\phi + 123\phi^2)$	(10)
Bahaya, Johnson [156]	Relativevelocity = $1 + (\eta)f = K(\eta)^{2f^2} + Of^3 + \dots$	(11)
Esfahani, Nunna [157]	$\frac{\mu_{nf} - \mu_{bf}}{\mu_{bf}} = C\mu\phi = > C\mu = \frac{(\mu_{nf})}{(\mu_{bf})} - 1$	(12)
Ahammed, Asirvatham [158]	$\mu_{nf} = \mu f(1 - \phi)^{2.5}$	(13)

nanoparticles assumes a significant role on rheological properties of nanofluids. The Viscosity for Graphene Oxide nanofluids at 0.01 and 0.5 wt%, temperature 25 °C, and shear pace 100 1/s increased about 38% and 130%. The increase in Viscosity with increment in concentration was additionally seen at higher temperature, however with little

decrease on scale. Viscosity measurements affirm that both the base liquid and prepared nanofluids are non-Newtonian in nature all through the deliberate temperature go. Viscosity increases by 100% that of base liquid at normal room temperature of nanofluid consisting 0.395 vol% f-HEG. Enhancement in viscosity is huge but its value is, nonetheless, extremely ostensible (12.1 cp), almost same as Ethylene Glycol at room temperature [153].

pH of the nanofluid

Yang, Ji [117] inspected the impact of Graphene Oxide/Water Nanofluid and exhibited nanofluid has maximum stability ideal at pH = 8. The prepared Nano-liquid sample utilized in estimating thermal conductivity had complete stability for about 6 months. According to [116] the zeta potential for a conc. of 0.2 mg/ml can reach to 50.9 mV at pH = 12.0, and the prepared nanofluids has great scattering stability for higher nanofluids temperature & added volume conc. The pH value of nanofluids is calculated by [80] has obtained 8 value, and having complete stability identified zeta potential is about 31.8, 40.9, and 45.7 mV for GNPs at 300, 500, and 750 m²/g.

The concentration of ionized groups on GO and r-GO sheets at different values of pH were determined using a Ph titration by the author. In the Fig. 19, red curve indicates that equilibrium is attained at each step of pH solution, delta indicates the difference in volume then as a function of pH same was performed for reduced Graphene Oxide.

Factors affecting thermal conductivity and viscosity

Analysis of thermal conductivity of Graphene-based nanofluid with different volume concentrations and temperature was shown in Fig. 20. Thermal conductivity is plotted against temperature. The corresponding thermal conductivity values and temperature values are: 0.6185 W/m-k at 50 °C with Graphene/Water Bharadwaj, Mogeraya [26], 0.627 W/m-k at 25 °C with Graphene Oxide/Water Nazari, Ghasempour [29], 0.710 W/m-k at 20 °C with Graphene/Water Zhao, Xu [159], 0.85 W/m-k at 60 °C with GONs/Water Yu, Xie [72], 0.53 W/m-k at 65 °C with GNP/Water-EG Arzani, Amiri [160].

We can conclude that the thermal conductivity of Graphene nanofluids enhances with an increase in temperature. Maximum value of 0.85 W/m-k is obtained at 60 °C at 0.85% vol concentration.

The variation of absolute viscosity for various temperatures at different volume concentrations and particle sizes is presented in

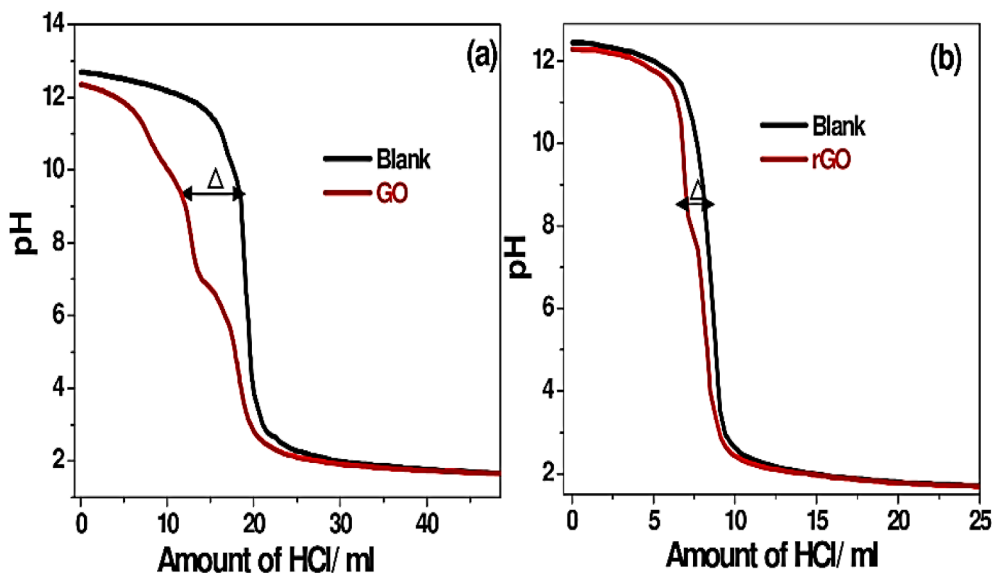


Fig. 19. pH of (a) Graphene Oxide (GO) and reduced GO [61].

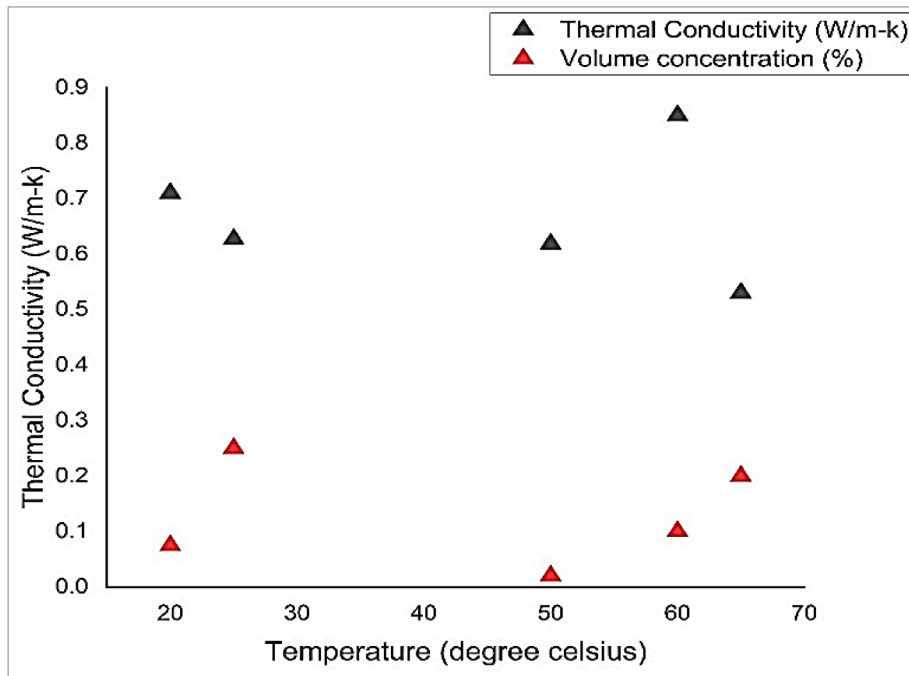


Fig. 20. Variation of Graphene-based nanofluid thermal conductivity, with the temperature at a different volume concentration.

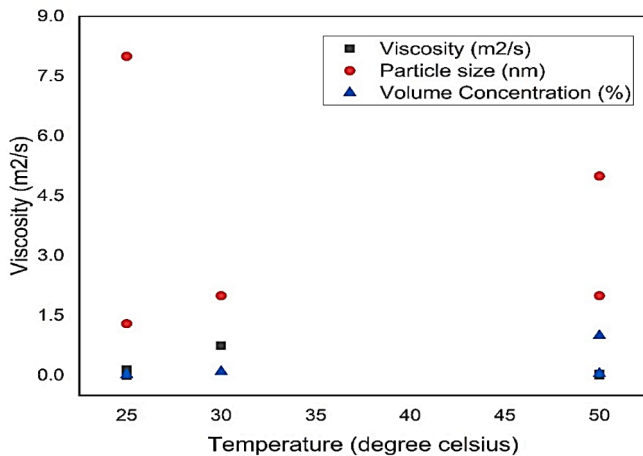


Fig. 21. Variation of absolute viscosity with the temperature at different volume concentrations and particle sizes.

Fig. 21. The viscosity, volume concentration and particle size were plotted against temperature, the corresponding values of viscosity, volume concentration, particle size and temperature considered for graphical representations are: 0.1565, 0.01%, 8 nm, 25 °C Park and Kim [147], 0.001805, 1%, 2 nm, 50 °C Bharadwaj, Mogeraya [26], 0.001042, 0.02%, 1.3 nm, 25 °C Akhavan-Zanjani, Saffar-Avval [161], 0.750, 0.1%, 2 nm, 30 °C Mehrali, Sadeghinezhad [162], 0.04712, 0.05%, 5 nm, 50 °C. The viscosity of the Graphene nanofluids increases with an increase in volume concentration and at lower temperatures, variation in dynamic viscosity is more than at higher temperatures. Below Tables 5 and 6 provides a detailed summary of various research studies involving Graphene-based nanofluids which shows Nanofluids exhibit high stability, high heat transfer coefficient, and enhanced thermal conductivity values when compared to base fluids, and Comparative analysis of the effect of volume concentration on thermal conductivity, viscosity of Graphene nanofluids.

The author Ponangi, Sumanth [27] studied experimentally and

identified the results which derives than base fluids, nanofluids will enhance the performance of an automobile radiator. It showed an extreme value of 56.45% and 41.47% thermal conductivity at 40 °C and 50 °C. Bahaya, Johnson [156] experimentally investigated thermal conductivity for GNP nanofluid and compared with water and identified that 1.43× at a volume fraction rate of 0.014. This presents the highest enhancement of thermal conductivity. Addition of GNP with mixture of water as well increases solution viscosities with an enhancement ratio of 33.1 for GNP nanofluids for volume fraction of 0.014. Ahammed, Asirvatham [158] experimentally measured Graphene water nanofluid viscosity and surface tension using SDSM as a surfactant and identified that viscosity of Graphene-water nanofluid increases with increase in vol. concentration with an average enhancement of 47.12% at 0.15% G for 50 °C. With temperature and vol. concentration increment, Surface tension in contrast has decreased by 18.7%. Summary of Graphene-based nanofluids of previous research for heat transfer application are provided in the Table 7.

Application of graphene based nanofluids as a coolant

The fulfilment of a heat engine is reliant on its cooling system and it is essential to develop an efficient cooling system to improve the performance. Radiator performance can be accelerated by using an active fluid which has good thermal characteristics such as Nanofluids [165]. Graphene-based nanofluids have excellent heat transfer and flow properties which enhances the thermal conductivity in nanofluids and act as an efficient coolant in a radiator [166]. Along with thermal conductivity, Graphene also improves the specific heat coefficient of nanofluids, viscosity, and density of nanofluids. Different applications of Graphene as a coolant and in electronic applications are reviewed by Yu and Xie [91]., and the effects of Graphene-based nanofluids as the electronic coolant is studied by Sharma and Gupta [110]. The heat transfer mechanism is fast and effective by adopting Graphene nanoparticles. Different parameters of Graphene nanoparticles such as the use of surfactants, smooth or rough surface conditions and thermal properties enhance the energy efficiency of the radiator by providing efficient heat transfer [167]. Graphene is also used in many applications such as defect sensors, biomedical, cosmetics, imaging, and capacitors [168-170]. The

Table 5
Summary of important findings and results of Graphene based nanofluids.

Nanoparticles	Base fluid	Application	Findings	Stability	Results	Ref.
Graphene Nanoribbon	Pure W	Heat Transfer Performance of an Automobile Radiator	Effectiveness, & overall HT coefficients - new generation vehicles could have more aerodynamic Design.	Stable	Highest enhancement obtained as 31.6% for GNR-water. Mean enhancement values of overall HT coefficients are 18.8% & 24.8%.	Kilinc, Buyruk [163]
Graphene Oxide (GO)	W: EG	NF can be used in Industrial applications as HT fluid in cold regions.	The results show TC of NF ↑with the amount of GO Nanosheets	Confirmed stability of NF	TC enhanced by 47% at 46.7 °C for water (40%)-ethylene glycol (60%) based GO (5%) NF.	Izadkhan, Erfan-Niya [128]
Graphene Oxide (GO) Graphene Nanoribbon (GNR)	Pure W	Vehicle Radiator (cross-flow heat exchanger)	The dimensions and weights of the vehicle cooling systems can be reduced	Stable	The mean enhancement values of U for all temperatures were 5.41% and 26.08% for GO/water NF and 15.62% and 20.64% for GNR/water NF	Kilinc, Buyruk [164]
Graphene Oxide	(60:40) DI W/EG	–	Improved results show stable NF	Stable	A max improvement in TC was about 6.67% to 10.47%	Ijam, Saidur [62]
Graphene Oxide	EG: W (50:50)	Radiator	Improved results say NF will enhance the performance of an Automobile Radiator compared to BF	Stable	Results shows maximum of 56.45% & 41.47% improvement for effectiveness	Ponangi, Sumanth [27]
Graphene Nano Platelets	W: EG (70:30)	Vehicle Radiator cooling system	GnP/H2O-EG NF could be better heat transfer fluid for Radiator cooling.	Stable	Overall HT coefficient increased by 104% with 0.5 vol% of GnP.	Selvam, Raja [53]

Table 6
Comparative analysis of the effect of volume concentration on thermal conductivity, viscosity of Graphene nanofluids.

Volume Concentration	Particle Size	Observations	References
0.01% of Graphene (M–5) and (M–15)	8 nm	The thermal conductivity value for M–5 Graphene nanofluid increased at rate of 5.47% compared to M–15 Graphene. The rate of increase in viscosity of M–15 Graphene nanofluid was 15.65% higher than M–5 Graphene nanofluid.	Park and Kim [147]
0.02% of Graphene-water nanofluid	1.3 nm	Thermal conductivity was enhanced remarkably after adding Graphene nanoparticles by 10% and Heat transfer coefficient was enhanced by 6.04%	Akhavan-Zanjani, Saffar-Avval [161]
0.1% of Graphene Nano platelet (GNP) nanofluids	2 nm	GNP nanofluid significantly enhances characteristics of heat transfer. The HTC was enhanced by 200% after adding GNP compared to distilled water.	Mehrali, Sadeghinezhad [162]
0.15% of Graphene and water nanofluid	5 nm	Viscosity value increased with increase of vol.conc. Viscosity was increased by 47.12% for 0.15% of the vol conc of Graphene at 50 °C.	Ahammed, Asirvatham [158]
1% of carboxyl Graphene and Graphene Oxide	2 nm	The effectiveness of the radiator in terms of thermal conductivity was improved by 10.5%, the heat transfer coefficient was enhanced at 193%.	Bharadwaj, Mogeraya [26]
0.05% and 0.2% of Graphene nanofluids	30 μm	Thermal conductivity was increased by 27%, 0.2% vol. conc. of Graphene nanofluid. A linear increase in electrical conductivity was observed with increase in particle volume concentration.	Gandhi, Velayutham [132]

Table 7
Heat transfer analysis on Graphene based nanofluids.

Material	Analysis	Observations	References
Graphene nanofluid	Stability analysis and thermal conductivity	Graphene enhances thermal conductivity by increasing nanoparticle concentration	Sadeghinezhad, Mehrali [6]
Carboxyl Graphene and Graphene Oxide	System Analysis of the radiator	Radiator efficiency was improved using Graphene based nanofluid compared to conventional coolants	Sumanth, Babu Rao [11]
Graphene Oxide	Analysis of thermal performance of pulsating heat pipe (PHP)	Thermal resistance of PHP was reduced up to 42% using Graphene Oxide	Nazari, Ghasempour [29]
Graphene nanofluid	Thermal conductivity and viscosity of nanofluids	Using 0.05 wt% Graphene instead of water can achieve 15.1% and 10.7% decrease in startup time	Zhao, Xu [159]
Graphene nanosheets and Graphene Oxide	Analysis of thermal conductivity of nanofluids using ethylene glycol as base fluid	Graphene and Graphene Oxide enhance thermal conductivity of base fluid upto 86% for 5% Graphene dispersion in base fluid	Yu, Xie [72]
Graphene nanoplates	Analysis of Rheological properties, specific heat capacity and thermal conductivity	Heat transfer Coefficient was improved using Graphene nanoplates than base fluid	Arzani, Amiri [160]

Fig. 22 representing the application of graphene.

Application of graphene in renewable energy technologies

Graphene is an atomic substance placed in a honeycomb lattice. It is a special material with many good features, including high mobility of the carrier. This unique material can be used in the application of renewable energy including fuel and solar cells, lithium-ion batteries,

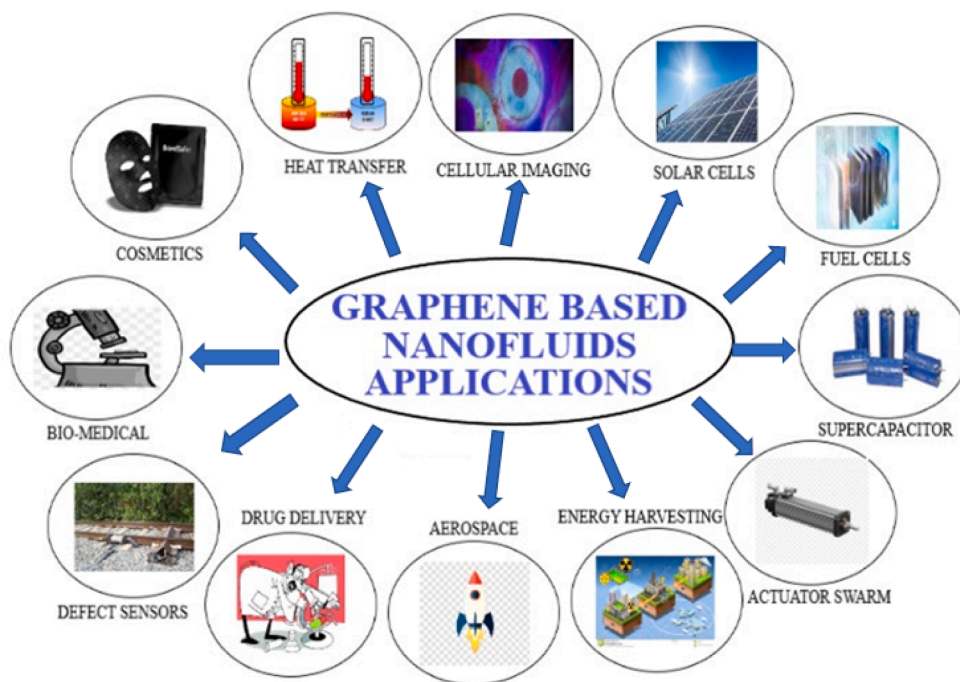


Fig. 22. Various applications of Graphene based Nanofluids.

supercapacitors etc. The details are provided in the following subsections.

Super-capacitor

Super-capacitors are electric power storage systems in portable electronic devices where incredibly fast charging is an important feature [171]. It offers high storage capacity, fast loading, and charging (within a few seconds) process, long life (generally > 100,000 cycles), need little maintaining, and lower self-discharging. In contrast to traditional capacitors, they have a greater power density [172]. Numerous studies claim that graphene is a much better capacitor material compared with

current both carbon-based and polymer-based materials. Relatively significant efforts have been made in super-capacitor research using pure graphene, and different metal-doped pure graphene, and carbon nanotube [173]. The findings of the graphene-based super-capacitor electrodes are shown in Fig. 23 [174-187]. However, it has been reported that the graphene-based (GA/TiO₂) electrode material offers strong specific capacitance (50–150 F/g) in 0.1 M NaCl solution under a variety of scanning rates ranges from 5 mV s⁻¹ to 1000 mV s⁻¹* [188]. After achieving a balance at 200 s, GA/TiO₂ based electrode showed a powerful desalination performance over 10 cycles, which was considerably better than those obtained by pure GA and neat activated carbon. The mass-produced GNSs with a small mesoporous distribution of 4 nm

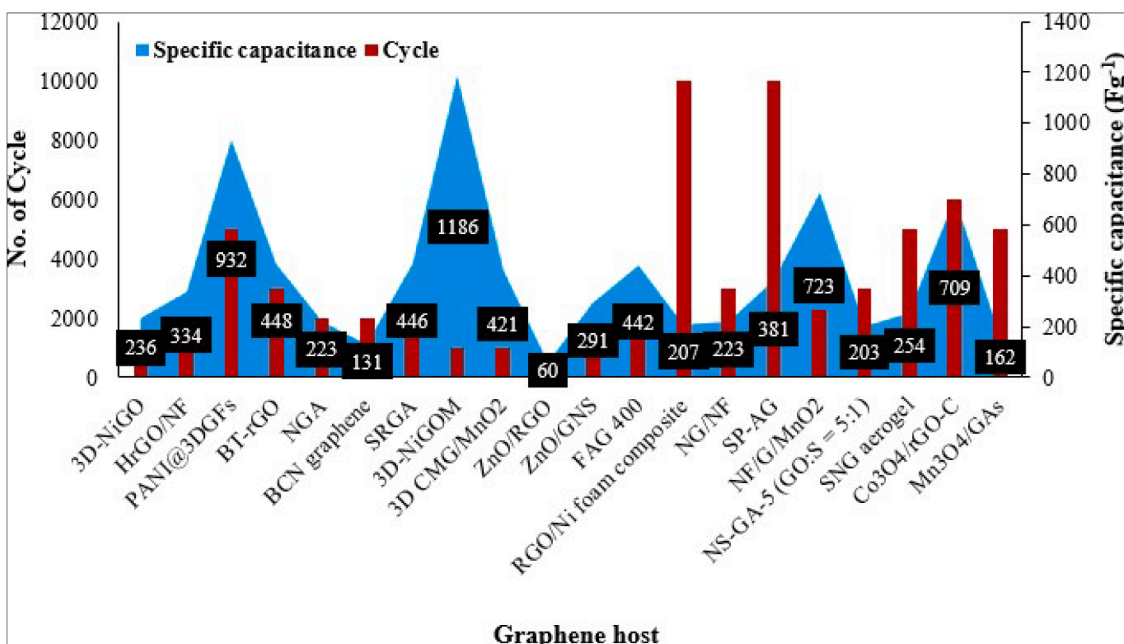


Fig. 23. Summary of the research findings (2015–2019) on the performance of graphene-based supercapacitor electrode [174-187].

from natural graphite through oxidization and quick heating has been researched by Du, Guo [189]. Their findings suggest that for 500 charging-discharging cycles, the GNS would retain the strong specific capacitance (150 F/g) at the specific current of 0.1 A/g [189]. Graphene has been tested as a possible super-capacitor electrode material by the researcher [190] and an outstanding cyclical capacity of $\sim 90\%$ resulting after 1200 cycles have been obtained.

Solar cells

The use of graphene in solar-based devices has special significance in the production of clean and renewable energies [191]. Chang, Liu [192] has produced a novel photo-electrochemical cell (PEC) based on graphene-based nanocomposites for converting the PV energy, and where its composites include a basic platform to transform solar power, photoconductivity, and photodetector. They have shown that the photocurrent generation and the PV conversion performance of PECs are considerably enhancing (over 10-fold) by using graphene in a POT film. Furthermore, graphene/POT's transmission resistance declined substantially by just 10% of pure POT, which indicates that graphene composite will serve as a successful solar power transmission platform in the long term. PECs were shown to rely largely upon graphene content and morphology, with the maximum efficiencies achieved in the nanocomposite with 5 wt% graphene content [192]. In addition to its wide surface as well as high electron mobility, the high capacity of graphene as an acceptor has also been significantly increased; all of these are important in enhancing the solar cell efficiency. However, the research on 2D graphic controlled DSSC output has shown high cell output such as Jsc (11.6–15.90 m), OCV (0.72–0.78 V) and efficiency (3.2–8.2%) percent while MOx/rGO is used with graphene oxide composition and photosensitive metal oxides. Fig. 24 shows a summary of the research findings (2015–2019) on the performance of graphene-based solar cell [193–198].

Battery/Lithium-ion storage

Lithium batteries are an additional class of energy storage technologies that employ graphene because of its recorded higher physical characteristics. Like super-capacitors, global demand is rising for advanced Li-ion batteries that have improved energy capacity and long

cycle life promising in terms of their use in electric vehicles [199]. Li-ion batteries may hold and produce power over a long period, in which electrode components play an important role in the operation, but every part of the battery is necessary for its efficiency. The anode material currently used in lithium-based batteries is typically graphene-based due to its high Coulombic performance [200]. Nevertheless, the comparatively low theoretical strength of the batteries (372 mAh/g) and the large diffusion ranges of the Li-ions should be overcome to increase the battery efficiency [200]. Graphene has since proven to be a good substitute for papers with graphene-based electrodes that have greater technical capabilities compared to other electrode materials [201]. Fig. 25 summary of the research findings (2015–2019) on the performance of graphene-based LIBs battery electrode [165,167,202–208].

Researcher [202] provided the most robust graphene-based anode materials for LIBs, with a 400-cycle discharge capacity and a current density of 500 mAh/g; the discharge capacity is 2–3 times higher than pure graphene aerogel. Sun, Mei [209] reported even greater stability using the LIBs anode with a 90% retention capability following 10,000 cycle operations, with using the Nb₂O₅ loaded hole graphene system. Although the basic discharge capacity was not very high (~ 150 mAh g⁻¹) in comparison with the N-GA of the Meng group (500 mAh/g) [202]. The HGF anode is used explicitly without any of the aid of binder and conductive added material, which demonstrated the advanced free-standing 3D bulk graph frames of the binder as the direct electrode for LIBs or green energy storage systems [209]. The significant difference in specific capability of the 2D Nb₂O₅/G (~ 60 mAh/g) control specimen against 3D Nb₂O₅/HGF-2.0 (145 mAh/g) was shown in this hypothesis in the same electrochemical study with the loading Nb₂O₅ (6 mgcm⁻¹).

Fuel cells

Battery and electrical fuel cell study is a major topic in sustainable energy production. The generation of electricity through electrochemical oxidation of alcohol sources of renewable energy from splitting water may help to reduce petroleum-based fuel requirements [201]. Besides, graphene-based materials are very common as an electro-catalyst, alongside the strong catalytic activity of fuel cell catalysts and simple modification characteristics of graphene with these materials. Researcher [210] have claimed that nitrogen-doped graphene behaves as a metal-free electrode that increases electro-catalytic efficiency;

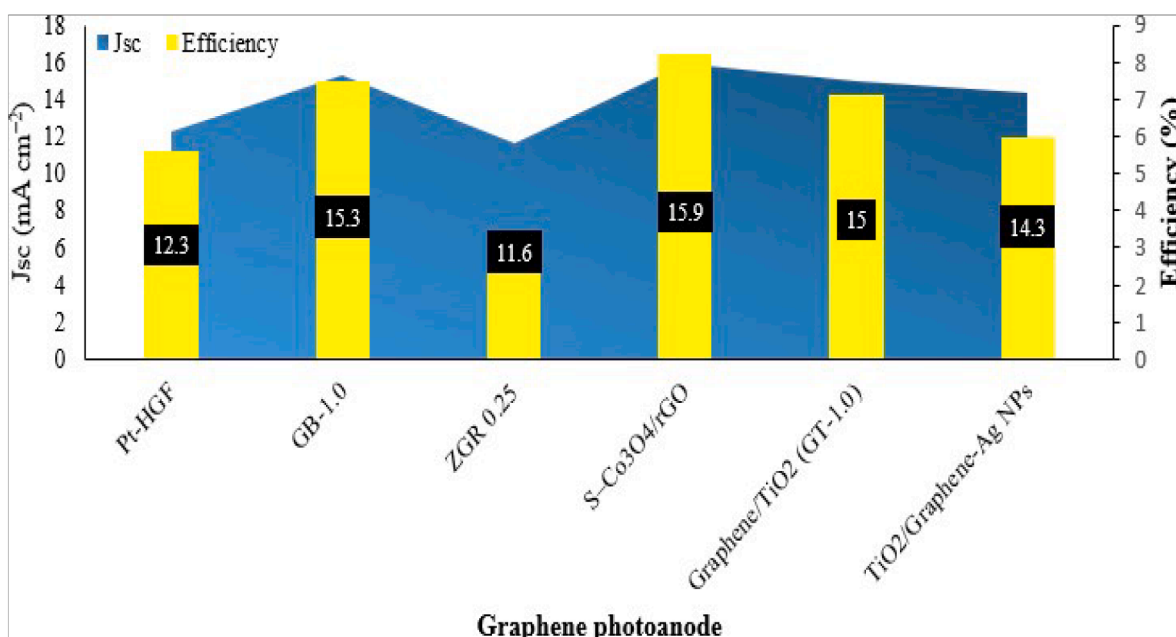


Fig. 24. Summary of the research findings (2015–2019) on the performance of graphene-based solar cell [193–198].

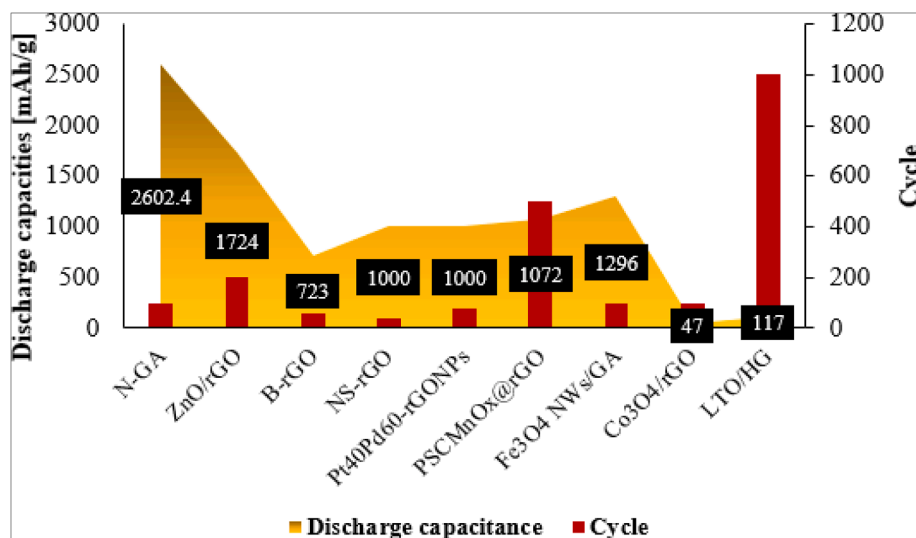


Fig. 25. Summary of the research findings (2015–2019) on the performance of graphene-based LIBs battery electrode [165,167,202–208].

possesses long-term durability of operation, and crossover resilience than Pt for the reduction of oxygen. However, graphene has also been correlated with the improved electro-catalytic function of the fuel cell. In particular, Xin, Liu [211] have reportedly shown that use of platinum/GNS (Pt/GNS) catalyst has shown excellent catalytic activity, in comparison to the Pt-supported carbon-black (C) activity for both methanol oxidation and ORR. Researcher [212] has shown that with the use of graphene supported Pt-Ruthenium (Ru) nanocomposite, better catalytic activity can be achieved for the oxidation of methanol as compared to the alternative Pt-Ru/Vulcan based material. Dong, Gari [213] have shown that Pt and Pt-Ru synthesized nanoparticles on GNSs have high electron-catalytic activity in the form of methanol and ethanol in contrast with graphite alternatives, resulting in a substantially reduced potential over-power and enhanced reversibility.

Challenges and future prospective

- There is big potential for advance research study on Graphene based nanoparticles in hybrid nanofluids.
- Need improved study on Stability of hybrid nanofluids when using Graphene based nanoparticles. Though there are various studies, still could not find a way to overcome agglomeration and sedimentation of nanoparticles. Size and shape of nanoparticles has become necessity for enhancing heat transfer performance which need to be overcome
- Graphene Quantum Dots (GQD) utilization in Nano medical applications has major scope.
- Recent studies show that Graphene flakes with cross linked polysilicon are playing crucial role in development of development of sensors and there is a need for detailed study on its application.
- Advance studies need to be performed for developing new synthesis methods which would permit easy production of Graphene with ideal structure.

Conclusion

The review article focuses on prominent attributes of Graphene nanofluids and their latest technological advancements in industrial applications. Various existing literature signifies that a large portion of the research focuses on stability, thermal conductivity, and heat transfer characteristics of Graphene nanofluids. The Graphene nanofluid preparation and stability are also discussed. The two step and the ultrasonication are the commonly used methods to dissolve Graphene-based nanoparticles in the base fluid to enhance heat transfer

properties of the fluid. From this conducted review, the ideal Graphene-based nanoparticle size is identified to be less than 50 nm and the best heat transfer base fluid to be mixed is water or water mixed with ethylene glycol. The minimum and maximum volume concentrations considered were between 0.001% and 2%. The concept of utilizing a Graphene-based nanofluids is influenced by the purpose of improving the heat dissipation of system. This study covers fundamentals of Graphene properties, preparation technique of Graphene nanofluids, stability analysis, and stability enhancement techniques, thermal properties of nanofluids and effect of Graphene nanofluids on thermal conductivity. Also, the effect of temperature on thermal conductivity and viscosity of the base fluid was discussed. It was observed from the existing literature that the thermal conductivity of base fluids was prominently improved by 86% with 5% dispersion of Graphene nanoparticles. Some prominent conclusions were made based on the literary works; the enhancement of thermal conductivity of nanofluids is dependent on temperature and thermal conductivity increases with increase in temperature, functionalized Graphene nanoparticles increase stability and durability of the nanofluids, suspension of Graphene nanoparticles in the base fluid increases the thermal conductivity of the base fluid. It was observed from the comparative analysis that addition of Graphene nanofluids significantly enhances viscosity and heat transfer capacity of base fluids. Viscosity was increased by 47.12% for 0.15% volume of Graphene nanoparticles and heat transfer coefficient enhanced by 193% for 1% of Graphene Oxide.

CRedit authorship contribution statement

Madderla Sandhya: Conceptualization, Methodology, Writing - original draft, Data curation. **D. Ramasamy:** Conceptualization, Supervision, Formal analysis, Visualization, Investigation. **K. Sudhakar:** . **K. Kadirgama:** . **M. Samyano:** . **W.S.W. Harun:** . **G. Najafi:** . **M. Mofijur:** . **Mohamed Mazlan:** Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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