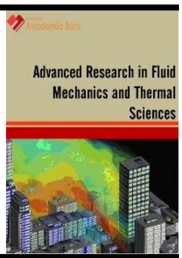
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Heat Transfer and Thermal Conductivity Enhancement using Graphene Nanofluid: A Review

Open Access

Ali Hilo[1], Abd Rahim Abu Talib[1,2,*], Sadeq Rashid Nfawa[1], Mohamed Thariq Hameed Sultan[2], Mohd Faisal Abdul Hamid[1], M.I Nadiir Bheekhun[3]

[1] Aerodynamic, Heat Transfer & Propulsion Group (AHTP), Department of Aerospace Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[2] Aerospace Malaysia Research Centre (AMRC), Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[3] Aerospace Science and Technology Research Group, Faculty of Information Sciences and Engineering, Management and Science University, 40100 Shah Alam, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 31 August 2018
Received in revised form 16 November 2018
Accepted 4 December 2018
Available online 13 March 2019

Keywords:
Thermal conductivity, Graphene, Graphene oxide, Nanofluid

ABSTRACT

Among other nanoparticles, higher thermal conductivity can be found in Carbon nanostructures due to the low density and intrinsic thermal conductivity in comparison with metals or metal oxides. This paper has reviewed the results of different experiments that were done to examine the heat transfer capabilities of graphene nanofluids. An overview summary of the latest graphene nanofluid's preparation methods in addition to some features that effect on the thermal conductivity such as viscosity, concentration, particles size and temperature has been provided. Furthermore, a critical review has been given to the convective heat transfer performances of graphene nanofluids. The paper showed that a significant result is found in using graphene nanofluids as a working fluid through tube channel to enhance heat transfer. In regard to the literature there is no study has been done on the influence of graphene nanofluids in facing step and corrugated.

1. Introduction

Due to the rapid development of science and the growing needs of industries to obtain rates of high heat transfer, many attempts have been done to reach for original approaches to enhance the rates of heat transfer. Despite the fact that various methods have been used effectively such as applying electric or magnetic fields changing the geometry and increasing the heat transfer surface, but they are still unable to fulfil the recent needs of heat flux dissipation and heat transfer.

It can be said that nanofluid is part of nanoparticles within a common working liquid such as water or ethylene glycol which is made in order to form an effective another working fluid meant for enhancing heat transfer [1]. However, there is a main concern when it comes to any technology that works with small size and high power, which is the heat removal and management. Therefore,

* *Corresponding author.*
E-mail address: abdrahim@upm.edu.my (Abd Rahim Abu Talib)

highlighting these issues by using nanofluids has drawn the attention of the scientist working in this field. Nanofluid can be deigned in many situations to fulfil a specific demand and it can play as pliant cooling method through its ability to adapt the need of particular system. Generally, nanofluids have the ability to be the major adjustable coolant in the world, as in various situations, they can play the role of flexible cooling method due to the fact that they can be designed to fulfil a specific inquiries, therefore, they have the ability of adjusting to the necessities of a specific system [2,3].

Various attempts have been done on properties of surfaces such as roughness, shape and extension as well as on the on heat transfer fluid and fluid motion whether the laminar or turbulent, to raise the fluid heat transfer coefficient. Recently, many studies have been done to investigate the preparation of nanofluids by using carbon based nanostructures [4]. One of the most materials that have been studied recently is the graphene [4], which can be defined as a single-atom-thick sheet of hexagonally arrayed sp2-bonded carbon atoms. Graphene has attracted the scientists' attention since its discovery by Novoselov *et al.,* [5], due to its significant electrical characteristics as its high transfer or mobility. Generally, carbon atoms are arranged in a ordered two sp2 orbitals bonded atomic-scale hexagonal shape which is considered as a main arrangement for other sp2 carbon bonded nanostructure material [6]. In the past few years, many studies have been looked at graphene because of its significant features (e.g. optical, electrical, thermal, mechanical etc.) [7]. In graphene research , graphene's characterization considered as vital part and includes measurements in regard to several spectroscopic and microscopic techniques [8]. In addition, studies have examined the significance of graphene nanoparticles and their advantages in comparison with other nanoparticles. These studies has stated that the graphene nanoparticles have various benefits such as better stability, lower corrosion, larger surface area/volume ratio, erosion and clogging, lower demand for pumping power, higher thermal conductivity and significant energy saving .

Therefore, this paper reviews some studies that were done to have an over view of the improved tribology and thermal conductivity (k) of graphene and oxide graphene nanofluids. Improvements and main issues related to synthesis, properties and characterization have been discussed too. Moreover, a critical review the results of the existing studies on thermal conductivity measurements and the convective heat transfer performances of graphene nanofluids is provided. The main parameters, which have an effect on the k, tribology and viscosity, have been clarified. Gaps were identified in previous research findings and recommendations for future researches were provided.

2. Synthesis of Nanofluids

Preparation method is the most essential part when it comes to the experimental investigation on nanofluids, which has to include two factors; the first is to be agglomeration free, while the other should be less sedimentation in the long time duration in real uses. Nanofluids are considered as a complicated combination of liquid and solid where the first is base fluid and the second is nanoparticle. However, in some kinds, the nanofluids need main requirements such as nanoparticles' trifling agglomeration, strong stable suspension and no chemical change of the base fluid. By providing particles in nano size in the base flued containing oil, water and ethylene glycol (EG), the Nanofluids manufactured. This process may be obtained by preparation method including one or two steps, such as graphene oxide for one-step preparation method and graphene nanoplatelets (GNP) nanofluid for two-steps preparation method [9]. However, these two methods have both advantages and limitations, and the method is determined by the production measure as well as the quality and purpose of groups needed for steady diffusion in to the targeted base fluid.

Graphene can be found in either multi-layers or single layers. Single-layer graphene is usually acquired from "highly ordered pyrolytic graphite" (HOPG) by micromechanical cleavage [5]. To obtain graphene in this method, a layer must remove the HOPG crystal, using transferred and scotch tape on to a silicon substrate. Furthermore, chemical methods can as well be used to prepare graphene through reducing the single-layer graphene oxide spreading in dimethlyformamide (DMF) by hydrazine hydrate [10]. There are several steps to produce the graphene nanofluid. The first one is use potassium suffocate salt to treating the graphene chlorine salt in methanol. The next step is to dialyze the product of the first step. This step is followed by the third step that is dissolving the product centrifuging it. While the final step is to discard the insoluble particles then collect and dry the supernatant liquid in order to get the solvent-free graphene nanofluid. Mehrali *et al.,* [11] have created nitrogen doped graphene with pristine graphene oxide by hydro-thermal treating in a Teflon lined autoclave with NH_3.

Additionally, highly stable graphene based nanofluids was proposed by Wang *et al.,* [12]. This was obtained when graphene oxide (GO) powder was separated into the Distilled water (DW) with assistance of hydrazine hydrate and ultrasonication was added into the combination. The process resulted in a solid product, which was washed by ethanol and Distilled water then exsiccated in a vacuum oven at 60°C for 24 hours to extract the remaining of solvent. Furthermore, Park *et al.,* [13] and Ghozatloo [14] have conducted a study to produce grapheme nanosheets. In order to do so, they tried to improve the graphene nanosheet on copper foil by catalytic putrefaction in a quarts tube furnace system. This was done by using Chemical vapor deposition (CVD). The next step was to functionalize the graphene by using potassium per sulphate and reflux system (see Figure 1), followed by mixing it with deionized water (DI). As a final step, the product was put in the ultrasonic bath for one hour in order for the graphene nanofluid to be prepared. Table 1 illustrates and summarizes the preparation of different graphene based nanofluid.

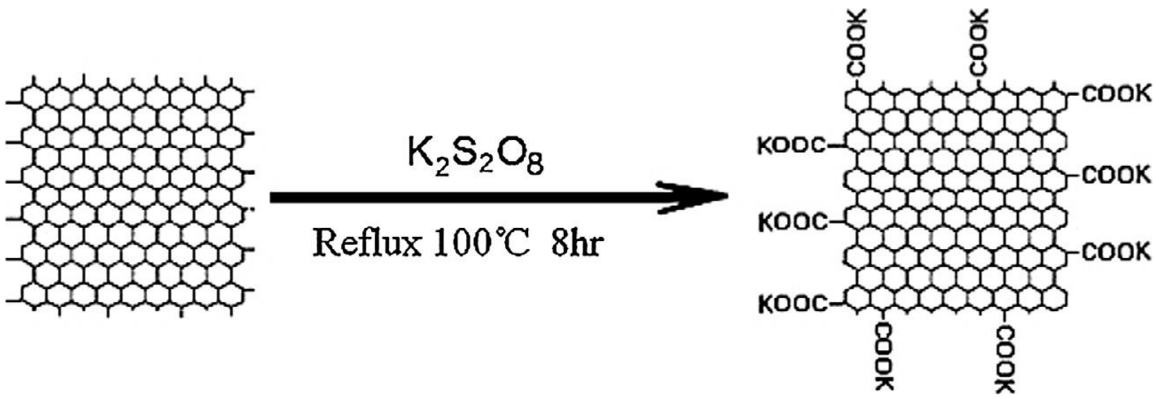


Fig. 1. Reaction scheme for the treatment of graphene using potassium per sulphate [14]

3. Stability

One of the big challenges that face the preparation of nanofluid is to get a homogeneous and stable nanofluid. The nanoparticles have the capability to aggregate because of the great van der Waals connection between them. Generally, the researchers use various techniques to enhance the nanofluid’s dispersion and to reduce the aggregation of particles that prevent long-term stability, including physical or chemical treatment. Nevertheless, it was reported that collecting and aggregation as features that help to boost nanofluid’s thermal conductivity. Thus, when it comes to the preparation, these issues must be considered if a balance is meant to be created between the stability of a nanofluid and thermal conductivity [26,27].

Table 1
Summary of graphene nanofluid preparation methods

Authors	Nanofluid	Preparation method	Concentration
Nazari *et al.,* [15]	Graphene oxide-water	Hummer method	0.25, 0.5, 1, and 1.5 g/lit
Akhavan-zangjani *et al.,* [16]	Graphene-water	Chemical method	0.02%
Sadeghinezhad *et al.,* [17]	Graphene nanoplatelets (GNP)- distilled water	The two step method	0.025, 0.05, 0.075, and 0.1 wt%
Mehrali *et al.,* [18]	Nitrogen-doped graphene/water	The two step method	0.01, 0.02, 0.04, 0.06 wt%
Zhang *et al.,* [19]	Graphene oxide-water	The two step method and chemical reduction methods	0.2, 0.4, 0.6, 0.8, and 1.0 mg/ml
Asirvatham *et al.,* [20]	Graphene-Acetone	Provided by manufacturer	0.05–0.09 vol%
Shende and Sundara [21]	Nitrogen-doped graphene /Ethylene glycol Deionized water	Graphene oxide prepared using Hummer method and the WNTs prepared using CVD	0.005–0.03 vol% 0.005–0.02 vol%
Ma *et al.,* [22]	Functionalized graphene nanosheets/Silicone oil	Hummer method then produced the material	0.0–0.07 wt%
Zhang *et al.,* [23]	Graphene oxide nanosheets - Distilled water	Provided by manufacturer	0.0001–0.0002 wt%
Ahammed *et al.,* [24]	Graphene-water	The two step method	0.05, 0.1 and 0.15%
Dhar *et al.,* [25]	Polydisperse Graphene- Distilled water	Hummer method and then produced the material	0.05–0.2 vol%

Surfactant has various types including "Sodium dodecyl sulphate (SDS), Oleic acid, Hexadecyltrimethylammonium bromide (CTAB), Gum Arabic (GA), Sodium octanoate (SOCT), Polyvinylpyrrolidone (PVP), Dodecyl trimethylammonium bromide (DTAB), Hexadecyl-trimethyl-ammonium bromide (HCTAB), and Triton X-100". These types may assist to adjust hydrophobic materials to allow dispersion in an aqueous solution. Or else, it would result a sedimentation, clogging and aggregation and leads to decrease the features of nanofluid which include thermal conductivity, viscosity, and increasing particular heat [11, 28, 29].

4. Thermal Properties

4.1 Experimental Results on Thermal Conductivity ($\boldsymbol{k}$)

One of the most significant studies of nanofluids is conducted on k due to its importance in the uses of heat transfer. Coolants have different base fluids with poor thermal conductivity, which needs considerable enhancement of its thermal properties. Carbon-based [30] particularly carbon nanotubes (CNT) nanofluids [31] were recognized to overtake all the metallic [32,33] and metal oxide [34] nanofluids innermost thermal conductivity. Though a theoretical thermal conductivity of $\sim 5000\ \mathrm{Wm^{-1}\ K^{-1}}$ is possessed by graphene [35] which is considered as more than the thermal conductivity of CNT [36].

Furthermore, the actual state and physical construction of each material is the base of the k, which is one of the thermal important features of a material; it has an essential part in various design issues. Thus, lots of effort have been put into describing and measuring thermal conductivity in the past [28,29]. Measuring thermos physical properties was a difficult task for a very long time as various techniques and methods proposed diverse outcomes. Therefore, the method intended to be adapted would be chosen to decrease the error in the measurement as far as possible. Additionally, thermal conductivity measurement has various methods like thermal comparator method, steady-state parallel-plate method, cylindrical cell method, thermal constants analyzer techniques, transient hot-wire techniques, and laser flash technique.

4.2 The Influence Volume Concentration on the Thermal Conductivity

Ethylene glycol and water have been commonly used as a base fluid in many studies in comparison with oil and various high-viscous fluids. Increasing in k was shown in both graphene [37,38] and grapheme oxide [9,39] with raising concentration which is so much alike the metal-oxide and metallic nanofluids [40,41]. In regards to explore chronological order, Yu *et al.,* [39] in 2010, proposed that the GO is able to improve the thermal conductivity of DW, propyl glycol and fluid paraffin nanofluids by 30.2%, 62.3% and 76.8% respectively using 5.0 vol%. While Ahammed *et al.,* [24] through his experimental research, have presented an improvement in the k of 37.2% for 0.15% volume concentration of graphene at 50°C in comparison with the same of the water at similar temperature.

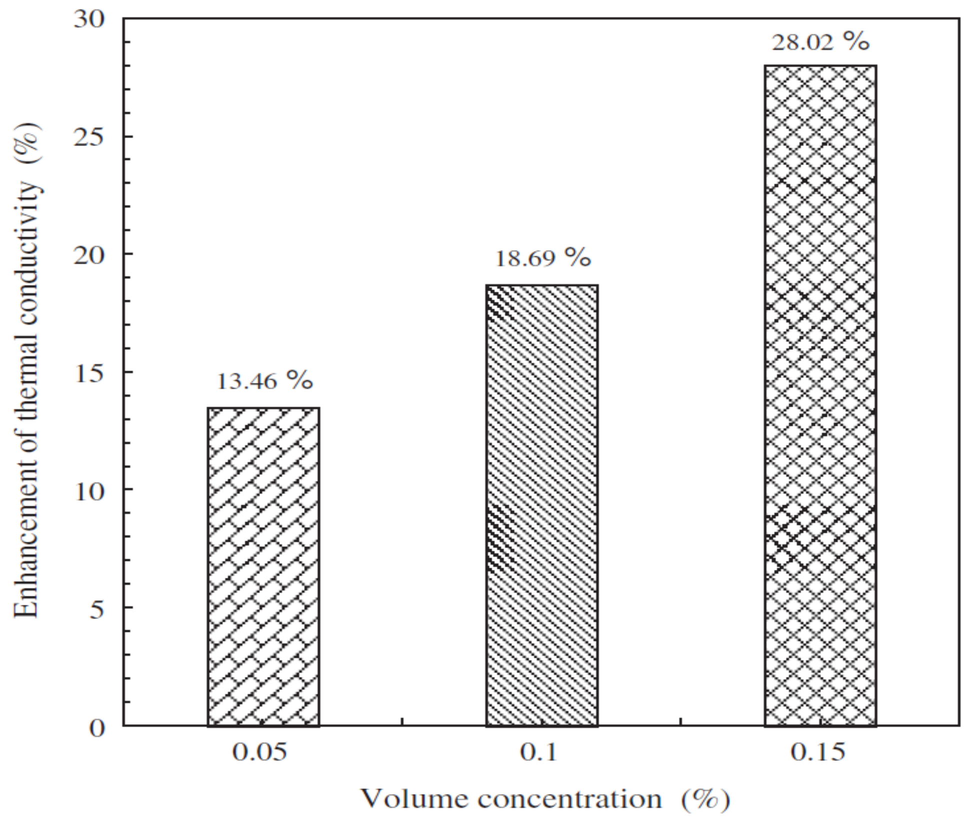


Fig. 2. The augmentation of k of graphene-water nanofluid via volume concentration [24]

Furthermore, something noteworthy from this research is that with the increase in temperature from 10-50°C, the percentage of the average k improvement with the increase in volume concentration from 0.05% to 0.15% is revealed to be 3.3% higher in comparison with that of the average improvement. Figure 2 illustrates the percentage improvement in differences of k of graphene–water nanofluid as a purpose of volume concentration for a constant average temperature of 30°C. It can be noticed that the improvement percentage in k of graphene water nanofluid has a direct proportion with increases with volume concentration. In other words, when the first increases the second increases too.

4.3 The Influence of Grapheme Size on Thermal Conductivity

It was reported that the nanoparticles' size and shape are an important thing when it comes to the k of nanoparticles suspensions as they depend heavily on them [34] and [42]. Esfahani *et al.,* [43] has reported that the thermal conductivity of graphene oxide nanofluids counts on two over, from Figure 3 it can be noticed that the increasing of the graphene oxide concentration leads to the increasing of the average particle size of GO nanofluids. A typical aggregate size increase from 600 nm to 1200 nm is resulted by the increasing the volume concentration from 0.01 wt.% to 0.1 wt.%. Lately Park *et al.,* [44] stated that the grapheme oxide with small average particle diameter is able to propose enhanced properties in comparison with other graphene nanofluids. Uniform sized graphene sheets' synthesis of remains as a challenging domain facing the scientists. Any further studies that may lead to better improvement in this domain could present a helpful chance to understand more the influence of size regarding this matter.

4.4 The Influence of Temperature on Thermal Conductivity

Based on kinetic theory, an increase of the energy of the particles and the base liquid molecules occurs with temperature increasing. The energy increasing would be obtainable for transfer from a place to another because of the particles' random motion. In 2003, Das *et al.,* [45] discovered that temperature is related to the anomalous k improvement of nanofluids as it depends on it. An improvement occurs in the k in most metallic, metal oxide and CNT based nanofluids when temperature is increased [45,46]. Hajjar *et al.,* [47] investigated the influence of GO nanofluid concentration and temperature on the k. The study results showed that for volume concentration 0.25 wt%, the improvement ratio is up to 31.0 at 10°C and enhanced to 47.5 when the temperature is increased to 40°C. Hence, it can be said that an improvement ratios increase in the thermal conductivity by temperature increasing which matches the results of other researches [9,45].
Another study was by Ahammed *et al.,* [24] conducted to examine the influence of temperature on the k of graphene-water nanofluids. These studies have come up with a result that an increase occurs to the k of nanofluid when the temperature and volume concentration of the nanoparticles is increased. Furthermore, it has been observed that an improvement in the k of 37.2% for 0.15% volume concentration of graphene in comparison with that of the pure water at 50°C temperature. Noteworthy that the mentioned studies [24,47], by applying the same condition, they have reached to almost the same results for thermal conductivity improvement 0.8 W/m.K (0.15 wt.% and 40°C) although different nanofluids were used (graphene oxide and graphene).

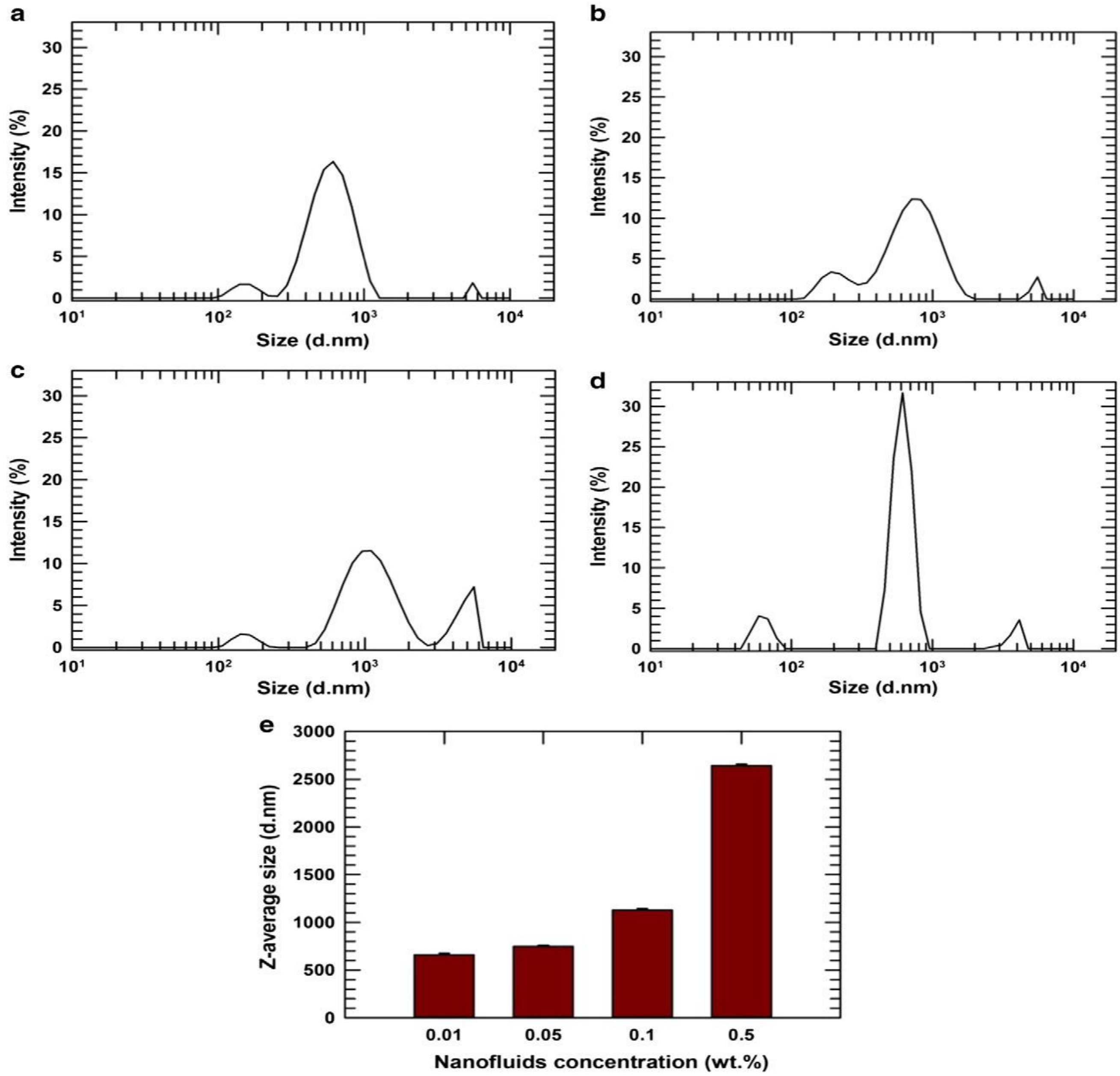


Fig. 3. Intensity based particle size distribution of graphene oxide (a) 0.01%, (b) 0.05%, (c) 0.1% and (d) 0.5%, (e) Z-typical size of all GO nanofluids at different volume concentrations [43]

5. Graphene Nanofluids Viscosity

Regarding the creating dynamic system for the uses of nanofluids' heat transfer, viscosity plays an important role, in addition to the fact that both the resulting of pumping power and the pressure drop are counting heavily on viscosity [2]. Limited studies have mentioned the rheological behaviour and looked deeply at graphene nanofluids compared to the studies conducted on thermal conductivity of graphene nanofluids. A great number of the studies done on the viscosity of nanofluid reported that a decrease occurs in the apparent viscosity with the increasing of the temperature. However, to investigate the flow behaviour of the liquids, various standard models are used such as law model, power Bingham plastic model and Herschel–Bulkley model [48].

Dhar *et al.,* [49] carried out a study on the graphene nanosheets viscosity and a comparison was done between the results of the study and CNT. In addition, Alumina nanoparticles were examined experimentally and numerically on viscosity of graphene nanosheets with various volume concentration (0.01–0.50 vol%) and temperatures (25–70°C). The results have highlighted that there is a similarity between the viscosity of graphene nanofluid and Einstein's formulation [49]. Park and Kim [44] examined the graphene M-5 and M-15 nanofluids viscosity at ambient temperature. The study showed that there is an increase in the rate of viscosity of the nanofluid graphene M-5 lower than the nanofluid graphene M-15. Furthermore, the graphene M-15 nanofluid had an increase of 15.65% at 0.01 vol% occurred to the viscosity have been recorded. Moreover, a study was done by Akhavan- Zanjani *et al.,* [50] to examine the viscosity of graphene–water nanofluid. The result showed that the viscosity's maximum increment is about 4.90% that happens at 0.02% volume concentration and 25°C temperature. Nevertheless, Kazi *et al.,* conducted a study on the viscosity of graphene oxide (GO) and graphene nanoplatelet (GNP) nanofluid [51]. At a low shear a tenfold increase in the viscosity was noticed in comparison to individual graphene oxide solution duo to the interaction appeared between participating colloids.

Nevertheless, there are not many studies have been done to examine the direct relation between k and viscosity of graphene nanofluids. Due to the fact that viscosity plays a significant role in affecting the nanofluids stability and heat transfer characteristics of nanofluid, thus, more studies are needed to have a better sight of the viscosity of graphene nanofluids.

6. Convective Heat Transfer Performance of Graphene Nanofluid

Plotting Nusselt number (*Nu*) is usually used to present the convective heat transfer (h) of nanofluids' experimental outcomes as a function of Reynolds number (*Re*). The influence of pumping power was examined by Sadeghinezhad *et al.,* [17] . The results showed that the GNP nanofluid had slight influence on the pumping power penalty. While Ghozatloo *et al.,* [52] have studied the measurement of the h coefficients of graphene nanofluids based on water under laminar conditions in the entrance region, Besides, they study has discussed the influence of volume concentration and the temperature on h coefficients of graphene nanofluids. In comparison with pure water, the h coefficient of graphene nanofluids at 38°C enhanced up to 35.6% at a concentration of 0.1 wt%. Moreover, factor of 1.77 for the thermal performance was found by sadeghinezhad *et al.,* [53]. The entropy generation analysis of nanofluids was investigated by both sadeghinezhad *et al.,* [53] and Mehrali *et al.,* [54], which is helpful for the heat exchangers to analyse the thermal design.

A different approach of stability for h coefficient was presented by Akhavan-Zanjani *et al.,* [50]. The stability of the graphene–water nanofluids by UV–Vis spectroscopy was studied by them. Furthermore, they examined the graphene water nanofluid two times; the first was one week before the experiments and the other was one week after them and it was found that both are except a slight sedimentations, it was almost stable. Another study was conducted by Mehrali *et al.,* [54] on the nanofluid stability by defining the deposition with centrifuge was examined. sadeghinezhad *et al.,* [55] have done a study on the heat transfer characteristics of GNP in both numerical method and experimental method. Nanofluids were investigated by them with both numerical and experimental aspects, besides, after experimental test, sedimentation photograph capturing method was used to examine the stability of nanofluid.

Experimental heat transfer caused turbulent and laminar flow for various forms of graphene nanofluids as illustrated in the studies that are featured in Table 2. Table 2 shows the types of nanofluid and testing parameters in addition to the heat transfer improvement ratio, which was used in the experiments.

Table 2
Convective heat transfer of graphene nanofluid

Author	Nanofluids	Geometry	Augmentation
Selvam *et al.,* [56]	Water-ethylene glycol mixture with graphene nanoplatelets.	Double tube	In the turbulent region the maximum augmentation of h coefficient is detected to be 170% at 0.5 vol%.
Selvam *et al.,* [57]	Graphene nanoplatelets (GNP)	Automobile radiator	The maximum augmentation of overall heat transfer coefficient is found to be 104% at 35°C.
Ghozaloo *et al.,*[52]	Graphene nanofluids	Circular tube	Augmentation in the local heat transfer coefficient up to 27.2%.
Ghozaloo *et al.,* [58]	EG/Graphene nanofluids	A copper pipe	The h coefficient increased up to 42.4%.
Sadeghinzhad *et al.,* [55]	GNP	Straight stainless steel tube	The h coefficient increase by 13-160%.
Baby and Sundara [59]	CuO/HEG	Straight stainless steel tube	Augmentation in h coefficient is 81–232%.
Baby and Ramapeabhu [60]	Ag/HEG	Straight stainless steel tube	Augmentation in h coefficient is 105-188%.
Mehrali *et al.,* [54]	GNP	Straight stainless steel tube	Augmentation in h coefficient up to 15%.
Hajjar *et al.,* [47]	Graphene dispersed nanofluids	A brass tube	The h coefficient increases up to 171%.
Akhavan-Zanjani *et al.,* [16]	Graphene nanofluid	Circular pipe	Augmentation in the heat transfer coefficient at *Re* = 1850 is 14.2%.
Yarmand *et al.,* [61]	Functionalized graphene nanoplatelets (f-GNP) nanofluids	Square tube	Maximum augmentation of overall heat transfer coefficient is 19.68% with 9.22% raise in friction factor.

In general, it is not easy to detect a standard theory to foresee precisely h characteristics of graphene nanofluids. Instead of using the two-phase mixture, many researches were done with the graphene nanofluids as single-phase fluid. Nevertheless, an important role should be played by the fluid and nanoparticle interaction and the motion between the fluids and the nanoparticle in influencing the h performance of graphene nanofluids.

7. Graphene Nanofluids through Tube Channel

In the course of recent years, it was found that nanofluids have the ability to extraordinarily enhance the k, stability and heat transfer coefficient as well as to decrease the wasted power and the costs [52]. These benefits led to increasing tendency to the use of nanofluids in various form of heat exchangers, because of the improved consumption of energy. Akhavan-Zanjani *et al.,* [16] have conducted a study to experimentally investigating the convective heat transfer coefficient of Graphene water nanofluid in a laminar flow through a circular tube with uniform wall heat flux [16], Maximum improvements are detected at 0.02% concentration. These improvements are 10.3% for thermal conductivity and 14.2% for heat transfer coefficient at *Re* of 1850. Furthermore, a circle tube with Nitrogen-doped graphene (NDG) nanofluids was used by Mehrali *et al.,* [18] in order to examine the properties of thermophysical under laminar flow. The study results showed that, in comparison with the base liquid, the k is improved for NDG nanofluids between 36.78% and 22.15%, and 7-50% increase in the heat transfer coefficient of the NDG nanofluids.

The graphene nanofluids was used by Ghozatloo *et al.,* [52], through the shell and tube heat exchanger under laminar flow. It was found that adding 0.075% of graphene to the base liquid helps to enhance the k up to 31.83% at saturation volume concentration of graphene as well as to improve the heat transfer coefficient that counts on the flow conditions. An experimental study was conducted by Sadeghinezhad *et al.,* [17] to look at the thermal, performance of a sintered wick heat pipe using aqueous GNP nanofluids. The study concluded with a result that the maximum efficient k improvements for the heat pipe at a GNP volume concentration of 0.1 wt% and a tilt angle of 60° for heat input rates of 20, 40, 60 and 80W are 23.4, 29.8, 37.2 and 28.3%, respectively, in comparison with a horizontal position ($\theta = °0$). However Yarmand *et al.,* studied the same nanofluid [61] by a square pipe at a constant heat flux, and the results showed that the improvement percentage is a function of weight concentration of nanoparticles and temperature. In comparison with the data from the base fluid, highest enhancement of total heat transfer coefficient is 19.68% with 9.22% increase in friction factor for the weight concentration of 0.1% at a *Re* of 17,500.

Zhou *et al.,* [62] have conducted an experiment to investigate the performance of heat transfer of oscillating heat pipes (OHPs) with grapheme nanoplatelet GNP nanofluids. In the mentioned experiments, the filling ratios were 45%, 55%, 62%, 70%, and 90%. It was found that an enhancement occurs to the heat transfer performance of OHPs by using GNP nanofluids as a comparison was made between the working fluid and an OHP with deionized water (DI). At suitable filling ratios (55%, 62%, and 70%), the best range of GNP nanofluid concentrations was found to be 2.0 – 13.8 vol%.

From the literature discussed above, it can be noticed that many studies have been done using different types of nanofluids in corrugated or facing step channels to analyses and investigate the effect of nanofluids inside the channel as working fluid. However, limited studies have been conducted to examine graphene nanofluids in such a channel, hence, further investigate on the graphene nanofluid may lead to understand more about its characteristic and influence on the heat transfer enhancement.

8. Conclusion

The literature survey shows that the graphene nanofluids have a significant effect on heat transfer and the thermal conductivity improvement. Regarding to the development of nanofluids, it is important to have a clear idea of the basics of heat transfer for a wide range of heat transfer application in order to be adapted in different uses of heat transfer. However, there are some improvements in investigating the heat transfer with graphene nanofluids. Nevertheless, it is required to conduct more experimental and theoretical studies of the particle movement to recognize the fluid flow behaviour and heat transfer of nanofluids. Moreover, in this review paper there are significant findings which are

i. The experimental results showed that graphene nanofluid has a significant effect on the heat transfer and thermal conductivity enhancement. Besides, the parameters that affect the thermal conductivity such as viscosity, particle size, concentration, and temperature have been studied and showed a high influence on the thermal conductivity enhancement. Another significant finding is that in most studies indicated that higher increase occurs in the thermal conductivity that the one occurs in convective heat transfer coefficient.

ii. There are some studies have been done on using graphene nanofluid in different shape of tube and all of them show a significant enhancement in heat transfer improvement. However, from the literature, it can be said that limited studies have investigated the effect of graphene nanofluid in facing step or corrugated channel.

iii. Most of the studies on graphene nanofluid performed at ambient temperatures. More experiments on the characteristics of graphene nanofluid in high temperatures are required to be done in order to have a better understanding of the behavior and heat transfer of graphene nanofluids and fill the gap in knowledge.

Acknowledgement
This work is supported under the Ministry of Higher Education Malaysia Fundamental Research Grant Scheme FRGS/TK05/UPM/02/7 no. 5524896.

References
[1] Choi, S. U. S. "Enhancing conductivity of fluids with nanoparticles, ASME Fluid Eng." *Division* 231 (1995): 99-105.
[2] Sadeghinezhad, Emad, Mohammad Mehrali, R. Saidur, Mehdi Mehrali, Sara Tahan Latibari, Amir Reza Akhiani, and Hendrik Simon Cornelis Metselaar. "A comprehensive review on graphene nanofluids: recent research, development and applications." *Energy Conversion and Management* 111 (2016): 466-487.
[3] Sidik, NA Che, and O. Adnan Alawi. "Computational investigations on heat transfer enhancement using nanorefrigerants." *Journal of Advanced Research Design* 1, no. 1 (2014): 35-41.
[4] Moghaddam, Monireh B., Elaheh K. Goharshadi, Mohammad H. Entezari, and Paul Nancarrow. "Preparation, characterization, and rheological properties of graphene–glycerol nanofluids." *Chemical engineering journal* 231 (2013): 365-372.
[5] Novoselov, Kostya S., Andre K. Geim, Sergei V. Morozov, D. A. Jiang, Y_ Zhang, Sergey V. Dubonos, Irina V. Grigorieva, and Alexandr A. Firsov. "Electric field effect in atomically thin carbon films." *science* 306, no. 5696 (2004): 666-669.
[6] Eatemadi, Ali, Hadis Daraee, Hamzeh Karimkhanloo, Mohammad Kouhi, Nosratollah Zarghami, Abolfazl Akbarzadeh, Mozhgan Abasi, Younes Hanifehpour, and Sang Woo Joo. "Carbon nanotubes: properties, synthesis, purification, and medical applications." *Nanoscale research letters* 9, no. 1 (2014): 393.
[7] Kumar, Vikas, Arun Kumar Tiwari, and Subrata Kumar Ghosh. "Application of nanofluids in plate heat exchanger: a review." *Energy conversion and management* 105 (2015): 1017-1036.
[8] Wong, King-Leung, José Luis León Salazar, Leo Prasad, and Wen-Lih Chen. "The inaccuracy of heat transfer characteristics for non-insulated and insulated spherical containers neglecting the influence of heat radiation." *Energy conversion and management* 52, no. 3 (2011): 1612-1621.
[9] Yu, Wei, Huaqing Xie, and Wei Chen. "Experimental investigation on thermal conductivity of nanofluids containing graphene oxide nanosheets." *Journal of Applied Physics* 107, no. 9 (2010): 094317.
[10] Gilje, Scott, Song Han, Minsheng Wang, Kang L. Wang, and Richard B. Kaner. "A chemical route to graphene for device applications." *Nano letters* 7, no. 11 (2007): 3394-3398.
[11] Mehrali, Mohammad, Emad Sadeghinezhad, Sara Tahan Latibari, Mehdi Mehrali, Hussein Togun, M. N. M. Zubir, S. N. Kazi, and Hendrik Simon Cornelis Metselaar. "Preparation, characterization, viscosity, and thermal conductivity of nitrogen-doped graphene aqueous nanofluids." *Journal of materials science* 49, no. 20 (2014): 7156-7171.
[12] Wang, Fuxian, Lijuan Han, Zhengguo Zhang, Xiaoming Fang, Jingjing Shi, and Wenshi Ma. "Surfactant-free ionic liquid-based nanofluids with remarkable thermal conductivity enhancement at very low loading of graphene." *Nanoscale research letters* 7, no. 1 (2012): 314.
[13] Park, Jae S., Kenneth D. Kihm, Honggoo Kim, Gyumin Lim, Sosan Cheon, and Joon S. Lee. "Wetting and evaporative aggregation of nanofluid droplets on CVD-synthesized hydrophobic graphene surfaces." *Langmuir* 30, no. 28 (2014): 8268-8275.
[14] Ghozatloo, Ahmad, Mojtaba Shariaty-Niasar, and Ali Morad Rashidi. "Preparation of nanofluids from functionalized graphene by new alkaline method and study on the thermal conductivity and stability." *International Communications in Heat and Mass Transfer* 42 (2013): 89-94.
[15] Nazari, Mohammad Alhuyi, Roghayeh Ghasempour, Mohammad Hossein Ahmadi, Gholamreza Heydarian, and Mohammad Behshad Shafii. "Experimental investigation of graphene oxide nanofluid on heat transfer enhancement of pulsating heat pipe." *International Communications in Heat and Mass Transfer* 91 (2018): 90-94.
[16] Akhavan-Zanjani, Hossein, Majid Saffar-Avval, Mohsen Mansourkiaei, Farhad Sharif, and Mohammad Ahadi. "Experimental investigation of laminar forced convective heat transfer of Graphene–water nanofluid inside a circular tube." *International Journal of Thermal Sciences* 100 (2016): 316-323.
[17] Sadeghinezhad, Emad, Mohammad Mehrali, Marc A. Rosen, Amir Reza Akhiani, Sara Tahan Latibari, Mehdi Mehrali, and Hendrik Simon Cornelis Metselaar. "Experimental investigation of the effect of graphene nanofluids on heat pipe thermal performance." *Applied Thermal Engineering* 100 (2016): 775-787.
[18] Mehrali, Mohammad, Emad Sadeghinezhad, Marc A. Rosen, Amir Reza Akhiani, Sara Tahan Latibari, Mehdi Mehrali, and Hendrik Simon Cornelis Metselaar. "Experimental investigation of thermophysical properties, entropy

generation and convective heat transfer for a nitrogen-doped graphene nanofluid in a laminar flow regime." *Advanced Powder Technology* 27, no. 2 (2016): 717-727.
[19] Zhang, Haiyan, Shanxing Wang, Yingxi Lin, Ming Feng, and Qibai Wu. "Stability, thermal conductivity, and rheological properties of controlled reduced graphene oxide dispersed nanofluids." *Applied Thermal Engineering* 119 (2017): 132-139.
[20] Asirvatham, Lazarus Godson, Somchai Wongwises, and Jithu Babu. "Heat transfer performance of a glass thermosyphon using graphene–acetone nanofluid." *Journal of Heat Transfer* 137, no. 11 (2015): 111502.
[21] Shende, Rashmi, and Ramaprabhu Sundara. "Nitrogen doped hybrid carbon based composite dispersed nanofluids as working fluid for low-temperature direct absorption solar collectors." *Solar Energy Materials and Solar Cells* 140 (2015): 9-16.
[22] Ma, Wenshi, Fang Yang, Jingjing Shi, Fuxian Wang, Zhengguo Zhang, and Shuangfeng Wang. "Silicone based nanofluids containing functionalized graphene nanosheets." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 431 (2013): 120-126.
[23] Zhang, Liang, Zitao Yu, Danyang Li, Liwu Fan, Yuanzheng Zhu, Ronghua Hong, Yacai Hu, Jianren Fan, and Kefa Cen. "Enhanced critical heat flux during quenching of extremely dilute aqueous colloidal suspensions with graphene oxide nanosheets." *Journal of Heat Transfer* 135, no. 5 (2013): 054502.
[24] Ahammed, Nizar, Lazarus Godson Asirvatham, Joel Titus, Jefferson Raja Bose, and Somchai Wongwises. "Measurement of thermal conductivity of graphene–water nanofluid at below and above ambient temperatures." *International Communications in Heat and Mass Transfer* 70 (2016): 66-74.
[25] Dhar, Purbarun, Soujit Sen Gupta, Saikat Chakraborty, Arvind Pattamatta, and Sarit K. Das. "The role of percolation and sheet dynamics during heat conduction in poly-dispersed graphene nanofluids." *Applied Physics Letters* 102, no. 16 (2013): 163114.
[26] Saidur, R., K. Y. Leong, and HaA Mohammad. "A review on applications and challenges of nanofluids." *Renewable and sustainable energy reviews* 15, no. 3 (2011): 1646-1668.
[27] Mehrali, Mohammad, Emad Sadeghinezhad, Sara Tahan Latibari, Salim Newaz Kazi, Mehdi Mehrali, Mohd Nashrul Bin Mohd Zubir, and Hendrik Simon Cornelis Metselaar. "Investigation of thermal conductivity and rheological properties of nanofluids containing graphene nanoplatelets." *Nanoscale research letters* 9, no. 1 (2014): 15.
[28] Sun, Zhenyu, Sascha Pöller, Xing Huang, Dmitrii Guschin, Christoph Taetz, Petra Ebbinghaus, Justus Masa *et al.,* "High-yield exfoliation of graphite in acrylate polymers: a stable few-layer graphene nanofluid with enhanced thermal conductivity." *Carbon* 64 (2013): 288-294.
[29] Goharshadi, Elaheh K., Yulong Ding, Majid Namayandeh Jorabchi, and Paul Nancarrow. "Ultrasound-assisted green synthesis of nanocrystalline ZnO in the ionic liquid [hmim][NTf2]." *Ultrasonics sonochemistry* 16, no. 1 (2009): 120-123.
[30] Ding, Yulong, Hajar Alias, Dongsheng Wen, and Richard A. Williams. "Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids)." *International Journal of Heat and Mass Transfer* 49, no. 1-2 (2006): 240-250.
[31] Choi, S. U. S., Z. G. Zhang, WLockwoodFE Yu, F. E. Lockwood, and E. A. Grulke. "Anomalous thermal conductivity enhancement in nanotube suspensions." *Applied physics letters* 79, no. 14 (2001): 2252-2254.
[32] Patel, Hrishikesh E., Sarit K. Das, T. Sundararajan, A. Sreekumaran Nair, Beena George, and T. Pradeep. "Thermal conductivities of naked and monolayer protected metal nanoparticle based nanofluids: Manifestation of anomalous enhancement and chemical effects." *Applied Physics Letters* 83, no. 14 (2003): 2931-2933.
[33] Lotfi, H., and M. B. Shafii. "Boiling heat transfer on a high temperature silver sphere in nanofluid." *International Journal of Thermal Sciences* 48, no. 12 (2009): 2215-2220.
[34] Li, Calvin H., and G. P. Peterson. "The effect of particle size on the effective thermal conductivity of Al 2 O 3-water nanofluids." *Journal of Applied Physics* 101, no. 4 (2007): 044312.
[35] Balandin, Alexander A., Suchismita Ghosh, Wenzhong Bao, Irene Calizo, Desalegne Teweldebrhan, Feng Miao, and Chun Ning Lau. "Superior thermal conductivity of single-layer graphene." *Nano letters* 8, no. 3 (2008): 902-907.
[36] Kim, Philip, Li Shi, Arun Majumdar, and Paul L. McEuen. "Thermal transport measurements of individual multiwalled nanotubes." *Physical review letters* 87, no. 21 (2001): 215502.
[37] Sen Gupta, Soujit, V. Manoj Siva, Sreenath Krishnan, T. S. Sreeprasad, Pawan K. Singh, T. Pradeep, and Sarit K. Das. "Thermal conductivity enhancement of nanofluids containing graphene nanosheets." *Journal of Applied Physics* 110, no. 8 (2011): 084302.
[38] Baby, Tessy Theres, and S. Ramaprabhu. "Investigation of thermal and electrical conductivity of graphene based nanofluids." *Journal of Applied Physics* 108, no. 12 (2010): 124308.
[39] Yu, Wei, Huaqing Xie, and Wei Chen. "Experimental investigation on thermal conductivity of nanofluids containing graphene oxide nanosheets." *Journal of Applied Physics* 107, no. 9 (2010): 094317.
[40] Eastman, Jeffrey A., S. U. S. Choi, Sheng Li, W. Yu, and L. J. Thompson. "Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles." *Applied physics letters* 78, no.

6 (2001): 718-720.

[41] Das, Sarit Kumar, Stephen US Choi, and Hrishikesh E. Patel. "Heat transfer in nanofluids—a review." *Heat transfer engineering* 27, no. 10 (2006): 3-19.

[42] Nasiri, Aida, Mojtaba Shariaty-Niasar, Ali Morad Rashidi, and R. Khodafarin. "Effect of CNT structures on thermal conductivity and stability of nanofluid." *International Journal of heat and Mass transfer* 55, no. 5-6 (2012): 1529-1535.

[43] Esfahani, Milad Rabbani, Ehsan Mohseni Languri, and Maheshwar Rao Nunna. "Effect of particle size and viscosity on thermal conductivity enhancement of graphene oxide nanofluid." *International Communications in Heat and Mass Transfer* 76 (2016): 308-315.

[44] Park, Sung Seek, and Nam Jin Kim. "Influence of the oxidation treatment and the average particle diameter of graphene for thermal conductivity enhancement." *Journal of Industrial and Engineering Chemistry* 20, no. 4 (2014): 1911-1915.

[45] Das, Sarit Kumar, Nandy Putra, Peter Thiesen, and Wilfried Roetzel. "Temperature dependence of thermal conductivity enhancement for nanofluids." *Journal of heat transfer* 125, no. 4 (2003): 567-574.

[46] Mintsa, Honorine Angue, Gilles Roy, Cong Tam Nguyen, and Dominique Doucet. "New temperature dependent thermal conductivity data for water-based nanofluids." *International Journal of Thermal Sciences* 48, no. 2 (2009): 363-371.

[47] Hajjar, Zeinab, Ali morad Rashidi, and Ahmad Ghozatloo. "Enhanced thermal conductivities of graphene oxide nanofluids." *International Communications in Heat and Mass Transfer* 57 (2014): 128-131.

[48] Karimi-Nazarabad, Mahdi, Elaheh K. Goharshadi, Mohammad H. Entezari, and Paul Nancarrow. "Rheological properties of the nanofluids of tungsten oxide nanoparticles in ethylene glycol and glycerol." *Microfluidics and Nanofluidics* 19, no. 5 (2015): 1191-1202.

[49] Dhar, Purbarun, Mohammad Hasan Dad Ansari, Soujit Sen Gupta, V. Manoj Siva, T. Pradeep, Arvind Pattamatta, and Sarit K. Das. "Percolation network dynamicity and sheet dynamics governed viscous behavior of polydispersed graphene nanosheet suspensions." *Journal of nanoparticle research* 15, no. 12 (2013): 2095.

[50] Akhavan-Zanjani, Hossein, Majid Saffar-Avval, Mohsen Mansourkiaei, Mohammad Ahadi, and Farhad Sharif. "Turbulent convective heat transfer and pressure drop of graphene–water nanofluid flowing inside a horizontal circular tube." *Journal of dispersion science and technology* 35, no. 9 (2014): 1230-1240.

[51] Kazi, Salim Newaz, Ahmad Badarudin, Mohd Nashrul Mohd Zubir, Huang Nay Ming, Misni Misran, Emad Sadeghinezhad, Mohammad Mehrali, and Nur Ily Syuhada. "Investigation on the use of graphene oxide as novel surfactant to stabilize weakly charged graphene nanoplatelets." *Nanoscale research letters* 10, no. 1 (2015): 212.

[52] Ghozatloo, Ahmad, Alimorad Rashidi, and Mojtaba Shariaty-Niassar. "Convective heat transfer enhancement of graphene nanofluids in shell and tube heat exchanger." *Experimental Thermal and Fluid Science* 53 (2014): 136-141.

[53] Sadeghinezhad, Emad, Mohammad Mehrali, Sara Tahan Latibari, Mehdi Mehrali, S. N. Kazi, Cheen Sean Oon, and Hendrik Simon Cornelis Metselaar. "Experimental investigation of convective heat transfer using graphene nanoplatelet based nanofluids under turbulent flow conditions." *Industrial & Engineering Chemistry Research* 53, no. 31 (2014): 12455-12465.

[54] Mehrali, Mohammad, Emad Sadeghinezhad, Marc A. Rosen, Amir Reza Akhiani, Sara Tahan Latibari, Mehdi Mehrali, and Hendrik Simon Cornelis Metselaar. "Heat transfer and entropy generation for laminar forced convection flow of graphene nanoplatelets nanofluids in a horizontal tube." *International Communications in Heat and Mass Transfer* 66 (2015): 23-31.

[55] Sadeghinezhad, Emad, Hussein Togun, Mohammad Mehrali, Parvaneh Sadeghi Nejad, Sara Tahan Latibari, Tuqa Abdulrazzaq, S. N. Kazi, and Hendrik Simon Cornelis Metselaar. "An experimental and numerical investigation of heat transfer enhancement for graphene nanoplatelets nanofluids in turbulent flow conditions." *International Journal of Heat and Mass Transfer* 81 (2015): 41-51.

[56] Selvam, C., T. Balaji, D. Mohan Lal, and Sivasankaran Harish. "Convective heat transfer coefficient and pressure drop of water-ethylene glycol mixture with graphene nanoplatelets." *Experimental Thermal and Fluid Science* 80 (2017): 67-76.

[57] Selvam, C., R. Solaimalai Raja, D. Mohan Lal, and Sivasankaran Harish. "Overall heat transfer coefficient improvement of an automobile radiator with graphene based suspensions." *International Journal of Heat and Mass Transfer* 115 (2017): 580-588.

[58] Ghozatloo, A., M. Shariaty-Niasar, and A. M. Rashidi. "Investigation of Heat Transfer Coefficient of Ethylene Glycol/Graphenenanofluid in Turbulent Flow Regime." *International Journal of Nanoscience and Nanotechnology*10, no. 4 (2014): 237-244.

[59] Baby, Tessy Theres, and Ramaprabhu Sundara. "Synthesis and transport properties of metal oxide decorated graphene dispersed nanofluids." *The Journal of Physical Chemistry C*115, no. 17 (2011): 8527-8533.

[60] Baby, Tessy Theres, and Sundara Ramaprabhu. "Enhanced convective heat transfer using graphene dispersed nanofluids." *Nanoscale research letters* 6, no. 1 (2011): 289.

[61] Yarmand, Hooman, Samira Gharehkhani, Seyed Farid Seyed Shirazi, Ahmad Amiri, Maryam Sadat Alehashem, Mahidzal Dahari, and S. N. Kazi. "Experimental investigation of thermo-physical properties, convective heat transfer and pressure drop of functionalized graphene nanoplatelets aqueous nanofluid in a square heated pipe." *Energy Conversion and Management* 114 (2016): 38-49.

[62] Zhou, Yu, Xiaoyu Cui, Jianhua Weng, Saiyan Shi, Hua Han, and Chengmeng Chen. "Experimental investigation of the heat transfer performance of an oscillating heat pipe with graphene nanofluids." *Powder Technology* 332 (2018): 371-380.