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A Comprehensive Review on Thermal Conductivity and Viscosity of Nanofluids

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ABSTRACT

The innovation of nanofluids, a novel working fluid, has presented the development of heat transfer properties in machining, automotive engine cooling systems, pumping power and others to optimize the overall system. Nanofluids have pulled in scientists' cogitation from various fields in designing new thermal systems for different engineering applications due to their distinctive thermophysical properties and prospective applications. Long term stability, improved thermal conductivity, and viscosity are the principal fundamental expectations in nanofluids research to achieve better heat transfer performance. In the previous couple of decades, various investigations have been completed to explore the nanofluids properties augmentation. For instance, kerosene-based oleic acid-coated Fe_3O_4 nanofluids showed 300% improvement of thermal conductivity, and water-based single-walled carbon nanotube revealed 320% improvement of viscosity. This paper presents a survey of recent exploration outcomes focusing on the thermal conductivity, viscosity, flow characteristics of hybrid nanofluids, including the preparation method of nanofluids utilized in different applications. Additionally, the elements that impact nanofluids' thermophysical properties, challenges of nanofluids, and fundamental outline and analysis of most recent research studies have been discussed and referenced. Finally, although the applications of nanofluid are increasing in several engineering sectors due to advanced discoveries of nanofluid, yet, requires more research focusing on the study of various sorts of nanofluids, different combinations of several types of nanoparticles, blending proportion and identifying the component which adds to the up-gradation of heat transfer to commercialize the nanofluids in practical fields.

Keywords:
Nanofluid; thermal conductivity; viscosity; concentration; temperature

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1. Introduction

The colloidal dispersion of nano-sized particles in the base fluid can be determined as nanofluid [1]. The nanoparticles have their principal dimension of less than 100nm [2]. Wong and De Leon [2] mentioned that the thermophysical properties, for example, thermal conductivity, diffusivity, viscosity and heat transfer coefficients of nanoparticles are enhanced due to dispersing the nanoparticles into a base fluid such as water, engine oil, vegetable oil, ethylene glycol, propylene glycol and so forth. So nanofluids can be used in machining, and they can be an unprecedented substitute for traditional cutting fluids [3]. The nanofluids' current progress in nanotechnology defines better cooling and lubricating media during machining because of its interesting and exciting heat transfer properties [4].

Moreover, anti-corrosion and anti-friction properties are also exhibited by nanoparticles [4]. Various materials can be used to synthesize nanoparticles. Different researchers experimented with preparing nanofluids using various metal and metal oxide nanoparticles such as pure Cu, CuO, Al_2O_3, TiO_2, SiC, SiO_2, Fe_2O_3, Fe_3O_4, ZnO, ZrO_2 for concentrations, mixing ratios and base fluids [5-10]. Besides, hybrid nanofluids, an extension of nanofluid, can be synthesized by dispersing more than one type of nanoparticles either in a mixture or a single type of base fluid [11]. The use of composite materials in hybrid nanofluids can combine physical and chemical properties, so it is rational to expect to achieve improved features from hybrid nanofluids compared with single nanofluids. For instance, kerosene-based Fe_3O_4-Graphene hybrid nanofluids showed more improvement in thermal conductivity than single Fe_3O_4 nanofluid [12]. Similarly, ethylene glycol (EG) based MgO-MWCNT hybrid nanofluids have more thermal conductivity than EG based MWCNT, SWCNT, and $Mg(OH)_2$ single nanofluids, respectively [13]. Hybrid nanofluids are associated with enhanced properties, and in some cases, it is more economical than single nanofluids [14]. However, nanofluids can be used in different practical fields for their outstanding features [15-18]. For example, Guo *et al.,* [19] states that composite materials containing carbon nanotubes (CNTs) have been utilized in bio-sensors, nanocatalyst and electrochemical-sensors. However, there are certain drawbacks, such as nanofluid agglomeration or flocculation in a short period, stability at high temperatures, and high viscosity. Therefore, the present review can boost understanding of advanced nanofluid, its preparation method and thermophysical features which can contribute to optimise the thermal performance of nanofluid. The principal objective of the present review is to (i) discuss the present state of the art nanofluid and the nanofluids are selected based on operating concentrations and temperatures in advanced engineering world, (ii) report the most significant and relevant studies conducted to enhance thermophyisical properties of nanofluid, (iii) represent various preparation techniques to obtain stable nanofluids and enhance their stability, (iv) present the challenges, problems and opportunities in the nanofluid study. The organization of the review articles is as follows- followed by the section of the introduction, Section 2 represents preparation or formulation methods of nanofluids, Section 3 emphasises the function of nanofluids as a coolant and lubricant the manufacturing world, Section 4 covers the comprehensive review on recent studies on the improvement of thermophysical properties in terms of thermal conductivity & viscosity of conventional fluid by adding various nanoparticles, Section 5 discusses on the challenges and opportunities as well and finally the conclusion section concludes the article with a comprehensive summary focusing future direction of study.

2. Preparation of Nanofluids

Usually, there are two techniques for synthesizing the nanofluids [18]; (i) One-step method and (ii) Two-step method. The one-step method consists of synthesizing the nanoparticles and suspending them in the base fluid simultaneously. The two-step method includes two parts; (i) Synthesis of the nanoparticles into powder form, (ii) Dispersion of nanoparticles into the base liquid to form a solution with uniformity and durability [20]. A one-step method is preferred to minimize agglomeration and to increase the stability of nanofluids. The one-step method is not appropriate for industrial purposes [20] because this technique is associated with higher production costs and only suitable for base liquids with less vapour pressure [21,22]. On the contrary, the two-step method is used in industries mainly due to its industrial level synthesis technique and lower production cost. However, under the two-step method, it is critical to desist from particles agglomeration [23]. The available literature shows that the two-step method is mostly dominant compared to the one-step method [24-30].

The one-step method is used for preparing nanofluids containing silica by Botha *et al.,* [31]. Al_2O_3/water nanofluid was also synthesized by employing a one-step method where cetyltrimethylammonium bromide (CTAB) surfactant was also added to achieve a homogenized solution [32]. In this study, the semi-spherical shaped nanoparticles were employed with the size of 11 nm, 25nm, 50nm and 63 nm diameter. Finally, the maximum enhancement of 14.26% of thermal conductivity derived from 63nm Al_2O_3 particles containing nanofluid. Cu nanofluid, a prospective coolant in heat transfer, was prepared by employing a single step [33]. In this investigation, diethylene glycol was the base fluid, and the working weight concentrations were 0.4%, 0.8% and 1.6%. The study found that nanofluid's durability was several weeks with the highest thermal conductivity from 1.6% weight concentration at 20°C. Moreover, in situ method was used to synthesize nanocomposite fluid by Sundar *et al.,* [34]. For this study, ferric chloride is added into the dispersion of water-based carboxylated-MWCNT and aqueous sodium hydroxide.

Au/water nanofluid was prepared by the one-step method, with a 48 % improvement of thermal conductivity [35]. In this investigation, it is also proved that thermal conductivity deteriorates with the rising size of particles. Similarly, Torres-Mendieta *et al.,* [36] also used the one-stage method for synthesization of Au nanofluid. Again, Paul *et al.,* [37] employed the one-step chemical method to prepare silver/water nanofluid and observed 21% improvement of thermal conductivity at 0.001M fraction. Under the widely employed two-step method after preparing the nanoparticles through various techniques, the nanoparticles are suspended into the base liquid [38]. Numerous researches have been conducted using this technique [39-47]. For instance, water-based TiO_2 nanofluid was synthesized by applying the two-step method, while the concentration range was from 0.1 to 2% [39]. Khairul *et al.,* [48] found a maximum 11% improvement of thermal conductivity, while the two-step technique was followed for sample preparation. SDBS surfactant was also added to homogenize the suspension. Water-EG based Cu: TiO_2 hybrid nanofluid was also synthesized by the two-stage method [49]. The mechanical mixture is used for nanoparticles dispersion at different concentrations, and sonication of the solution was done by an ultrasonic processor, which prevented nanoparticles agglomeration in the solution. HPLCwater-EG based CuO nanofluid showed 60% improvement of thermal conductivity while PVP and SLS surfactants were included in the solution with a total of 5 hours stirring and 2 hours sonication through employing the two-step method [43]. On the other hand, Yarmand *et al.,* [50] used acid treatment by suspending graphene (GNP) nanoparticles into the HNO_3 and H_2SO_4 solution ultrasonication process. Moreover, Esfe *et al.,* [51] employed a pH adjustment method to include dispersant and sonication methods for preparing stable nanofluid.

Harandi *et al.,* [52] also used the two-step method by mixing the same proportion of dry f-MWCNTs and Fe_3O_4 particles in ethylene glycol. X-ray diffraction was utilized to measure the basic properties of MWCNTs and Fe_3O_4 nanoparticles. After magnetic stirring, sonication was done for every sample to get stability and finally found all samples with moderate stability. EG based Fe_3O_4-Ag, oil-based MWCNT-ZnO, deionized water-based Al_2O_3-CuO hybrid nanofluids were also synthesized through repeating the same two-stage method by Afrand *et al.,* [53], Asadi and Asadi [54] and Ramachandran *et al.,* [55], respectively. Many other researchers also followed this double-stage method for synthesizing carbon nanotube containing nanofluids [56-58]. Water-based Ti_3C_2 nanofluid was also prepared using magnetic stirring for 30 minutes and then ultrasonication for 1 hour while SDBS was included as a surfactant [59]. Similarly, TiO_2-Al_2O_3/water-EG hybrid nanofluid was synthesized flowing the same two-step technique while forty-five minutes of magnetic stirring was done followed by seven hours of ultrasonication of colloidal suspension of nanoparticles [60]. However, the two-step method is especially recommended by Eastman *et al.,* [61] for preparing nanofluids consisting of oxide nanoparticles rather than metallic particles based nanofluids.

3. Nanofluids as Coolants & Lubricants

It is evident from the literature that traditional cutting fluids used in industries demonstrate poor performance compared with solid particles [62,63]. So, the need for improved heat transfer fluids leads researchers and scientists to look for new heat transfer fluids with a superior cooling capacity [17,64]. The addition of nanoparticles ameliorates the base fluid's thermal properties, and the superiority of nanoparticles is because of their sizes which occurs no blocking in the stream section [65]. Besides, most of the solid particles have more excellent thermal conductivities than conventional liquids, and during sliding lubricants with solid particles, they exhibit very minimal friction [66]. The improved thermal conductivity of traditional fluids because of including solid particles is one of the potential reasons for the applicability of nanoparticles suspension as nanofluid [67]. Patole and Kulkarni [68] mentioned that the inclusion of nanofluid with conventional Minimum Quantity Lubrication (MQL) system can be an unexampled substitute to flood coolant system because of its better cooling and lubricating properties. In this investigation, the use of ethylene glycol-based multi-walled carbon nanotube (MWCNT) nanofluid exhibit better surface integrity, less tool wear through maintaining temperature and cutting forces while turning AISI4340. Similarly, in the case of oil-based Al_2O_3, less cutting force and torque are needed to drill aluminium 6063 compared with traditional cutting fluid, and from this experiment, less surface roughness of workpiece and tool wear are derived with low friction force [69]. Uysal *et al.,* [70] also explored that maximum 19.9% tool wear reduction is possible by applying vegetable oil-based MoS_2 nanofluid with minimum surface roughness.

From previous investigations, it is found that the application of nanofluids exhibits significant thermal conductivity enhancement, other heat transfer properties and also heat absorption rate [5,6,71-76]. Moreover, the inclusion of nanoparticles (e.g., CuO, MoS_2, TiO_2, SiO_2, Al_2O_3 and diamond and others.) into the base fluid improves the anti-wear and load-carrying capacity of base fluid [66,77,78]. Choi *et al.,* [79] experimented with mixed nanofluids and found 3% reduction in electric power consumption by using mixed nanofluids (graphite and Ag nanoparticles). For the rolling effect of sphere-like nanoparticles, a significant reduction in friction coefficient is exhibited using nanofluids [80]. In this experiment, Al_2O_3 and MoS_2 were dispersed in deionized water and canola oil, respectively. The application of nanoparticles in the contact zone helps separate rubbing surfaces; thus, nanofluids show better anti-wear behaviour. Finally, nanofluids' application will direct to produce a new class of engineered fluids with superior properties that can effectively replace the traditional fluids.

4. Properties of Nanofluids

The two most significant features of nanofluids are thermal conductivity and viscosity, which have been reviewed in this paper for the last few years. Based on the literature, nanofluids with long-term stability, highest thermal conductivity, and the lowest dynamic viscosity can exhibit heat transfer's best performance.

4.1 Thermal Conductivity

Thermal conductivity is the most fundamental characteristic in the field of heat transfer of nanofluid [81]. Numerous researchers experimented to discover the behaviour of thermal conductivity by suspending nanoparticles in base liquid. In most cases, the application of nanoparticles in the base liquids substantially improves the thermal conductivity of base liquids [24,28,72,73,82-84]. Philip *et al.,* [10] found 300% improvement of thermal conductivity at 6% volume concentration by scattering oleic acid-coated Fe_3O_4 nanoparticles into kerosene through the application of a magnetic field of 82G. Keblinski *et al.,* [85] found enhancement of Cu nanoparticles' thermal conductivity for ethylene glycol and oil with the dispersion of less than 1% volume concentration of Cu nanoparticles. So, from different experiments from 1.1, 200% and maximum 300% enhancement of thermal conductivity is achieved [71,10,86]. Gavili *et al.,* [71] achieved the most significant thermal conductivity improvement by dispersing 50 nm-sized Fe_3O_4 nanoparticles in water.

Sundar *et al.,* [87] examined the characteristics of water-based and EG- water-based (20:80, 40:60 and 60:40) nanodiamond and ferric oxide (ND- Fe_3O_4) nanofluids using 0.05%, 0.1% and 0.2% volumetric fraction of nanoparticles in the range of temperature 20°C to 60°C. Water-based ND-Fe_3O_4 hybrid nanofluids showed better thermal conductivity than EG-water based nanofluids. A mixture of EG- water-based hybrid nanofluids 40:60 showed higher thermal conductivity followed by 60:40 and 20:80 mixtures. Hence, this study revealed that the base liquid's thermophysical properties determine the thermal conductivity of hybrid nanofluids. At the particle-fluid interface, the heat transfer in suspension occurs through the particles in the fluid, and more efficient thermal conductivity comes from an enhancement in the interfacial area- this is the explanation for the improvement in thermal conductivity of hybrid nanofluids. This study also revealed that the hybrid nanofluids' thermal conductivity could not be predicted by Maxwell and Hamilton-Crosser theory. Finally, the researchers also showed a new relationship concerning a progressive increment of thermal conductivity with the concentration of nanoparticles expressed in Eq. (1).

$$\frac{K_{nf}}{K_{bf}} = a + b\phi \qquad (1)$$

where a and b are constants for different temperatures, which are mentioned in Table 3.

At low mass concentration (0.05%), Fe_3O_4-Graphene showed little thermal conductivity improvement, but the thermal conductivity was higher (31%) at a mass concentration of 1% and 50°C temperature compared with kerosene as base fluid, while the hybrid nanoparticles average diameter was 261 nm [12]. Moreover, in hybrid nanofluids, the thermal conductivity shows higher enhancement than single Fe_3O_4 nanofluids. Askari *et al.,* [12] revealed the formation of the cluster of

Fe_3O_4-Graphene as a conceivable reason behind the improvement of thermal conductivity. In this investigation, when the particle concentration is higher, the temperature showed a critical effect on thermal conductivity compared with Esfe's *et al.,* [88] experiment. Therefore, it is revealed that the impact of temperature was intensive on the movement of the particles.

Thermal conductivity of hybrid nanofluids increases with increasing nanofluids' concentration and temperature during an investigation of SWCNT-MgO/EG hybrid nanofluids using 0.05, 0.075, 0.1, 0.25, 0.5, 0.75, 1.0, 2.0 vol% concentration of nanoparticles in the range of temperature 30-50°C [88]. In this study, the ratio of SWCNT and MgO was 20:80. Compared with other volume concentration intervals, the 1-2% volume concentration of nanoparticles showed a drastic drop in thermal conductivity because most of the particles are agglomerated for their interconnection. Moreover, 2% volume concentration does not show any substantial impact on thermal conductivity. So, this concentration does not apply to thermal applications. It is also derived from the research that the value of the thermal conductivity of hybrid nanofluids (SWCNT-MgO/EG) is in the middle range of thermal conductivity of SWCNT and MgO single nanofluid. Esfe *et al.,* [88] proposed a new relationship of thermal conductivity concerning concentration and the temperature of nanoparticles with regression coefficient, R^2= 0.9818, which is presented in Eq. (2).

$$\frac{K_{nf}}{K_{bf}} = 0.90844 - 0.06613\o^{0.3}T^{0.7} + 0.01266\o^{0.31}T \tag{2}$$

The higher concentration of nanoparticles results in the declension of the distance between particles because of the percolation effect, e.g., more particles are getting connected by increasing the lattice vibration frequency [88]. Hence, graphene nanoplates silver (GNP-Ag) nanofluids' thermal conductivity is enhanced with nanoparticles' rising temperature and concentration. Moreover, graphene nanoplate/platinum (GNP-Pt) showed the highest thermal conductivity enhancement of 17.77% at 0.1 % mass concentration and 40°C, while the investigation was conducted in the range of mass concentration of 0.02, 0.06 and 0.1% for temperatures ranging from 20°C-40°C [89]. The thermal conductivity showed a nonlinear relationship to temperature and concentration. In both experiments, Yarmand *et al.,* [88,89] found that the effective thermal conductivity of Pt, Ag and GNP nanoparticles promotes the thermal conductivity of hybrid nanofluids.

Esfe *et al.,* [90] revealed that at high temperature, better thermal conductivity with less viscosity of hybrid nanofluids could be achieved during optimization of water-based nanodiamond- cobalt-oxide ((ND: Co_3O_4) hybrid nanofluids by comparing results of NSGA-II method using Design Expert Software. However, the effects of various base oil, e.g., SAE oil, paraffin oil, vegetable oil, on the thermal conductivity of Cu-Zn hybrid nanofluids containing the same proportion (50:50) of Cu and Zn nanoparticles was investigated by Kumar *et al.,* [91] at 30°C. Three volumetric concentration of particles of 0.1%, 0.3%, 0.5% were used for conducting this experiment. Vegetable oil-based Cu- Zn hybrid nanofluids showed higher thermal conductivity, trailed by paraffin oil and SAE oil-based Cu-Zn hybrid nanofluids, respectively. The authors summarised that the better thermal conductivity of vegetable oil (*k*= 0.162W/mK) compared with paraffin oil's thermal conductivity (*k*= 0.136W/mK) and SAE oil (*k*= 0,133W/mK) and the internal repellent force of the fluid to flow are the reasons behind the improvement of thermal conductivity.

Sundar *et al.,* [92] studied water-based, ethylene glycol-based properties and the mixture of EG-water based (20:80, 40:60 and 60:40) ND – Co_3O_4 hybrid nanofluids using 0.05%, 0.10% and 0.15% vol% concentration under the range of temperature 20°C to 60°C. The results showed the higher value of thermal conductivity in hybrid nanofluids than single Co_3O_4 nanofluid by comparing with Mariano *et al.,* [93] experiment and the enhancement of temperature and thermal conductivity of

Co_3O_4 nanofluid decreases but the thermal conductivity of ND- Co_3O_4/EG nanofluid increases. The researchers found the improvement of thermal conductivity for hybrid nanofluids because of rising temperature and solid particles' concentration and as in Sundar *et al.,* [87] investigation on ND-Fe_3O_4 nanofluids. Water-based ND–Co_3O_4 hybrid nanofluids showed maximum thermal conductivity, trailed by EG and a mixture of EG-water based nanofluids. Nanoparticles concentration and temperature are both related to thermal conductivity, but this study developed a correlation (Eq. (3)) concerning the only concentration of nanoparticles mentioning that temperature has less impact on thermal conductivity at the lower concentration of solid particles.

$$\frac{K_{nf}}{K_{bf}} = 0.9978\,(1 + \text{ø}^{0.6556}) \tag{3}$$

However, both EG and water-based SiO_2-Cu hybrid nanofluids showed enhancement in thermal conductivity with increasing nanoparticles' concentration, increasing temperature, and the surface functionalization of SiO_2 with only approximately 8% copper nanoparticles [94]. Measurements were conducted under 0.25%, 0.50% and 1.0% volumetric concentration of particles and temperatures from 20°C up to 40°C. Vafaei *et al.,* [13] experimented using MgO-MWCNTs/EG hybrid nanofluids for 0.05%, 0.1%, 0.15%, 0.2%, 0.4% and 0.6% volumetric concentrations of nanoparticles within the range of temperature of 25°C– 50°C. The authors concluded that thermal conductivity increases with an increasing fraction of nanoparticles and decreases with increasing temperature. Finally, an equation of thermal conductivity depending on temperature and concentration of nanoparticles with 0.8% deviation was developed from this experiment, which is expressed in Eq. (4).

$$\frac{K_{nf}}{K_{bf}} = 0.9787 + \exp\,(\,0.3081\text{ø}^{0.3097} - 0.002T) \tag{4}$$

The higher quantity of hybrid nanoparticles showed lower heat conductivity improvement than low volume concentration because of the increasing dimension of clusters at higher volume concentration while researching the thermal conductivity effects of EG-based hybrid nanoparticles (MgO-FMWCNT) [95]. In this study, a comparison of the thermal conductivity was made between single and hybrid nanofluids, and the observation was MgO-FMWCNT/ EG hybrid nanofluids' thermal conductivity value was higher than that of MWCNT/EG, SWCNT/EG, Mg $(OH)_2$/EG single nanofluids. Finally, for MgO-FMWCNT/ EG hybrid nanofluids, Afrand proposed a new correlation (Eq. (5)) with higher accuracy (R^2= 0.99 and ME = ±1.2%).

$$\frac{K_{nf}}{K_{bf}} = 0.8341 + 1.1\text{ø}^{0.243}T^{0.289} \tag{5}$$

Shahsavar *et al.,* [96] found that with the enhanced temperature and an ultrasonic time, the thermal conductivity of hybrid nanofluids rises. They also discovered a suitable period of ultrasound beyond which the thermal conductivity drops while experimenting using Fe_3O_4–CNT nanoparticles along with gum arabic and tetramethylammonium hydroxide. From this experiment, thermal conductivity is improved up to 34.26% at 55°C.

Moreover, Thermal conductivity is also associated with the nanofluid's stability [97]. In this study, three types of synthesis techniques are used using pure MWCNTS and modified MWCNTS while the size of pure MWCNTS and modified MWCNTS were 37 µm (PS50), 804 nm (S50) and 335nm (SF50) respectively for preparing hybrid nanofluids. Finally, 21% improved thermal conductivity of MWCNT-ɣ-Al_2O_3 hybrid nanofluids is derived from the investigation, which is synthesized using 804nm (S50) sized functionalized nanoparticles.

Temperature, size, type and volume fraction of nanoparticles affect the nanofluids' thermal conductivity. Ahmadi *et al.,* [98] applied an artificial neural network and least square vector machine to investigate the thermal conductivity ratio model using alumina/water nanofluid expressing through temperature, size of particles, and volumetric concentration. In this study, among three applied algorithms, e.g., LSSVM, Levenberg-Marquardt Back Propagation and Self-Organizing Map, LSSVM shows the best results with a correlation coefficient of 0.89999 for thermal conductivity ratio of water-based Al_2O_3 nanofluid. Finally, it is also concluded that with growing concentration and temperature, the value of the heat conductivity ratio rises. The arrangement of particles appropriation in the composite structure will prompt the conduction impact through the materials because of the contact zone; in this way, it is relied upon to improve the heat transfer by the Brownian movement [99]. Hamid *et al.,* [47] noticed 10.1–13.8% improvement of thermal conductivity for 20:80 mixture ratio of TiO_2–SiO_2/water-EG nanofluid while minimum enhancement of thermal conductivity of 5.3–8.4% is derived from 50:50 mixture ratio of TiO_2–SiO_2.

Esfe *et al.,* [14] reported 20.1% improvement of thermal conductivity at 50°C while investigating the behaviour of SiO_2-MWCNT (70:30 ratio)/EG nanofluids. A new relationship with the R^2 value of 0.9864 is derived from this experiment for predicting the thermal conductivity ratio. Another model for predicting thermal conductivity ratio is modelled using an artificial neural network design (ANN), which shows higher precision for predicting thermal conductivity ratio with 0.9989 R-squared value. It is also evident that hybrid nanofluids could be more economical than the single nanofluid by comparing the price performance of hybrid nanofluids with oxidized and nanotube containing nanofluids separately. An increase in nanoparticles' concentration and temperature can be attributed to nanoparticles' better thermal conductivity compared with base oil while investigating the efficiency of thermal properties of MWCNT and Al_2O_3/thermal oil nanofluids at temperature 25-50°C and 0.125 to 1.5% solid concentration. Maximum 45% increase in nanofluid thermal conductivity is obtained from a concentration of 1.5% and 50°C. Finally, a new correlation is proposed by Asadi *et al.,* [100], which is expressed in Eq. (6).

$$K_{nf} = 0.1534 + (0.00026)T + 1.1193ø \tag{6}$$

Zadkhast *et al.,* [101] were carried out experimentally that the measured water-based MWCNT-CuO nanofluid' heat conductivity at distinct levels of concentrations and temperatures ranging from 0.05 to 0.6% and 25 to 50°C respectively through using KD2 Pro instrument with 0.1°C precision hot water bath. The impact of temperature on thermal conductivity is more distinguishable at higher volume fractions, and the most significant improvement of thermal conductivity was 30.38% at 0.6% volume concentration and 50°C temperature. Moreover, at 25°C, the thermal conductivity improvement was 7.3 to 25.57%, and at 50°C, the thermal conductivity improvement was 9.61 to 30.38 at 0.05 and 0.6% concentration, respectively. Finally, they concluded that rising temperature and solid concentration could enhance the thermal conductivity and proposed a new relationship (Eq. (7)) for 0.05 to 0.6% volume concentration and 25 to 50°C temperature with the multiplicative temperature and concentration function.

$$\frac{K_{nf}}{K_{bf}} = 0.907 \exp(\, 0.36\, ø^{0.3111} + 0.00095T) \tag{7}$$

Maximum 22.8% improvement of thermal conductivity was observed at 80°C by Nabil *et al.,* [28] while studying the properties of TiO_2–SiO_2 /water-EG nanofluid for volume concentration from 0.5 to 3% and temperature from 30 to 80°C and a regression correlation (Eq. (8)) of thermal conductivity was proposed which is applicable for 30 to 70°C up to 3% volume concentration. After that, Nabil *et al.,* [41] concluded that TiO_2–SiO_2 nanofluids' thermal conductivity is enhanced with an increment of temperature and concentration of particles. This improvement happens because the interaction among particles is more at higher temperatures and influences the electromotive force for the upgrade of thermal conductivity. Moreover, Xu *et al.,* [102] found 10.5%, 16.7%, 22.8% improvement of thermal conductivity of water-based Al_2O_3 nanofluid at 0.2 wt%, 0.5 wt% and 1 wt% using improved steady flow method (ISFM) under uniform heat flux condition. During estimation, the effect of natural convection is lessened by the ISFM method and thus prompts improving the estimating precision of the thermal conductivity fundamentally. Rubbi *et al.,* [103] prepared soybean oil-based MXene (Ti_3C_2) nanofluid dispersing two-dimensional MXene particles at weight concentrations of 0.025-0.125% while the Ti_3C_2/SO nanofluid revealed 60.82% thermal conductivity enhancement at 55°C and 0.125 wt% concentration. Hence, the results also concluded with 24.49% augmentation of heat capacity of nanofluid compared to base oil and 84.25% improvement of thermal effectiveness of PV/T system due to application of MXene nanofluid.

$$\frac{K_{nf}}{K_{bf}} = \left(1 + \frac{\emptyset}{100}\right)^{5.5} \left(\frac{T}{80}\right)^{0.01} \tag{8}$$

In another study, MXene nanofluid was synthesised using silicone oil as base fluid, while Transient Hot Bridge 500 was used to measure the thermal conductivity [104]. The authors found that thermal conductivity was enhanced by 64% at 0.1 wt% and 150°C. The study also showed that MXene/silicone oil nanofluid showed thermal homogeneity up to 380°C which can be a great achievement in the thermal engineering world. However, TiO_2-Al_2O_3/water-EG nanofluid revealed 40.86% enhancement of thermal conductivity at volume concentration of 0.1% and at 80°C while the considered concentrations were 0.02, 0.04, 0.06, 0.08 and 0.1% [60]. The study also compared the thermophysical properties of hybrid nanofluids with single nanofluids (TiO_2 and Al_2O_3) and stated that hybrid nanofluids exhibited better thermal conductivity and heat transfer efficiency than single nanofluids. Table 1 and Table 2 present the experimental results and responsible reasons behind the enhancement /deterioration of the thermal conductivity of nanofluids studied in recent years. Most of the study reveals that the concentration of nanoparticles and temperature mostly influences thermal conductivity. Besides, it is dependent on sonication time, particle size, the inclusion of other particles, interfacial area, and so forth. Table 3 presents the proposed correlations of thermal conductivity. From the studied literature, it is found that all the proposed relationships by researchers are authentic for a specific type of particles and sometimes also for a particular temperature. These correlations may not be applicable for measuring the thermal conductivity of other nanofluids with different ratios, particle size, and so forth.

Table 1
Summary of exploratory results of thermal conductivity of various nanofluids

Authors	Nanofluids	Other Information	Changes in Thermal Conductivity
Sundar *et al.,* [87]	ND-Fe_3O_4 /water	$0.05 < \phi \leq 0.2\%$ $20^\circ C \leq T \leq 60^\circ C$	17.8% improvement in thermal conductivity at 0.2 vol.% and 60°C.
Sundar *et al.,* [87]	ND-Fe_3O_4/EG/Water (20:80)	$0.05 < \phi \leq 0.2\%$ $20^\circ C \leq T \leq 60^\circ C$	13.4% improvement at 0.2% vol. con. and 60°C.
Sundar *et al.,* [87]	ND-Fe_3O_4/EG/Water (40:60)	$0.05 < \phi \leq 0.2\%$ $20^\circ C \leq T \leq 60^\circ C$	13.6% enhancement at 0.2 % vol. con. and 60°C.
Sundar *et al.,* [87]	ND-Fe_3O_4/ EG/Water (60:40)	$0.05 < \phi \leq 0.2\%$ $20^\circ C \leq T \leq 60^\circ C$	14.6% increments at 0.2% vol. con. and 60°C.
Askari *et al.,* [12]	Fe_3O_4-Graphene/ kerosene	$0.05 < \phi \leq 1\%$ $25^\circ C \leq T \leq 50^\circ C$	31.0% enhancement at 1.0% wt. con. and 50°C.
Esfe *et al.,* [88]	SWCNT-MgO (20:80)/ Ethylene glycol	$0 < \phi \leq 0.02\%$ $30^\circ C \leq T \leq 50^\circ C$	18.0% increment at 2.0% wt. and 50°C.
Yarmand *et al.,* [89]	GNP–Ag/ water	$0.02 < \phi \leq 1\%$ $20^\circ C \leq T \leq 40^\circ C$	22.22% enhancement at 0.1% wt. and 40°C.
Yarmand *et al.,* [89]	NP-pt/ water	$0.02 < \phi \leq 0.1\%$ $20^\circ C \leq T \leq 40^\circ C$	17.7% improvement at 0.1% wt. and 40°C.
Kumar *et al.,* [91]	Cu-Zn (50: 50)/ vegetable oil, paraffin oil, SAE oil	$0.1 < \phi \leq 0.5\%$; 30°C,	
Sundar *et al.,* [92]	ND-Co_3O_4/water	$0 < \phi \leq 0.0015$ $20^\circ C \leq T \leq 60^\circ C$	15.7% improvement at 0.15 wt% and 60°C.
Sundar *et al.,* [92]	ND-Co_3O_4/ Ethylene glycol	$0 < \phi \leq 0.0015$ $20^\circ C \leq T \leq 60^\circ C$	8.71% improvement at 0.15 wt% and 60°C.
Sundar *et al.,* [92]	ND-Co_3O_4/ EG/Water (20:80)	$0 < \phi \leq 0.0015$ $20^\circ C \leq T \leq 60^\circ C$	13.4% increment at 0.15 wt% and 60°C.
Sundar *et al.,* [92]	ND-Co_3O_4/ EG/Water (40:60)	$0 < \phi \leq 0.0015$ $20^\circ C \leq T \leq 60^\circ C$	11.3% increment at 0.15 wt% and 60°C.
Sundar *et al.,* [92]	ND-Co_3O_4/ EG/Water (60:40)	$0 < \phi \leq 0.0015$ $20^\circ C \leq T \leq 60^\circ C$	10.1% improvement at 0.15 wt% and 60°C.
Amiri *et al.,* [94]	SiO_2-Cu/ water	$0.25 < \phi \leq 1\%$ $20^\circ C \leq T \leq 40^\circ C$	15.9% enhancement at 1.0 vol% and 40°C.
Amiri *et al.,* [94]	SiO_2-Cu/EG		18% increment at 1.0 vol% and 40°C.
Afrand [95]	MgO-FMWCNT/ EG	$0.05 < \phi \leq 0.6\%$ $25^\circ C \leq T \leq 50^\circ C$	21.3% increases at 0.6 vol% and 25°C.
Shahsavar *et al.,* [96]	Fe_3O_4–CNT/ water		34.26% increases at 2.428 wt% Fe_3O_4–1.535 wt.% CNT and 55°C.
Abbasi *et al.,* [97]	MWCNT-γ-Al_2O_3/ water		20.68% increases at 0.1 vol% and 25°C.
Hamid *et al.,* [99]	TiO_2-SiO_2 (20:80, 40:60, 50:50, 60:40 and 80:20)/ Water-EG	$\phi = 1\%$; $30^\circ C \leq T \leq 70^\circ C$	Max.10.1–13.8% improvement of thermal conductivity for TiO_2-SiO_2 (20:80) and min. 5.3–8.4% increment for TiO_2-SiO_2 (50:50).
Esfe *et al.,* [14]	MWCNT-SiO_2 (30:70%)/ EG	$0.025 < \phi \leq 0.86\%$; $250^\circ C \leq T \leq 50^\circ C$	20.1% increases at 50°C and at vol. con. 0.86%.
Asadi *et al.,* [100]	Al_2O_3-MWCNT/ Thermal oil	$0.125 < \phi \leq 1.5\%$ $25^\circ C \leq T \leq 50^\circ C$	Max. 45% improvement at 1.5% vol. con. and at 50°C.
Zadkhast *et al.,* [101]	MWCNT-CuO/ Water	$0.05 < \phi \leq 0.6\%$ $25^\circ C \leq T \leq 50^\circ C$	Max. 30.38% increment at vol. con. of 0.6% and at 50°C, Max. 25.57% at 0.6% vol. con. 25°C.
Nabil *et al.,* [28]	TiO_2-SiO_2/ water-EG(60:40)	$0.05 < \phi \leq 3\%$ $30^\circ C \leq T \leq 80^\circ C$	Max. 22.8% enhancement of thermal conductivity at 3.0% vol. con. And at 80°C.
Xu *et al.,* [102]	Al_2O_3/water	$0.2 < \phi \leq 1\%$ $20^\circ C \leq T \leq 90^\circ C$	10.5%, 16.7%, 22.8% improvement at 0.2 wt.%, 0.5 wt.% and 1 wt.%.

Table 2
Summary of responsible reasons behind changes in the thermal conductivity of various nanofluids

Authors	Nanofluids	Reasons
Sundar *et al.,* [87]	ND-Fe_3O_4/water; EG-water (20:80), (40:60), (60:40)	Thermal conductivity can be improved by increasing the interfacial area and can also be influenced by sonication time.
Askari *et al.,* [12]	Fe_3O_4-Graphene/kerosene	Cluster development of nanoparticles is a conceivable explanation for the improvement of thermal conductivity.
Esfe *et al.,* [88]	SWCNT-MgO (20:80)/Ethylene glycol	Interaction of nanoparticles directs to the thermal conductivity improvement.
Yarmand *et al.,* [89]	GNP–Ag/ water	The thermal conductivity increases with the rising concentration of particles and rising temperature.
Yarmand *et al.,* [89]	NP-pt/ water	GNP-Pt hybrid nanofluids' high thermal conductivity is because of the high thermal conductivity of GNP and Pt, and the thermal conductivity of GNP-Pt is nonlinear with mass concentration and temperature.
Kumar *et al.,* [91]	Cu-Zn (50: 50)/ vegetable oil, paraffin oil, SAE oil	The internal resistance of the fluid to flow can enhance thermal conductivity.
Sundar *et al.,* [92]	ND-Co_3O_4/water; Ethylene glycol; EG-water (20;80), (40:60), (60:40)	The micro-convection between water molecules and nanoparticles results in an increase in thermal conductivity with increasing temperature.
Amiri *et al.,* [94]	SiO_2-Cu/ EG; Water	Thermal conductivity can be improved by surface-functionalized SiO2 with 8% copper addition and increased by growing concentration and temperature of nanoparticles.
Vafaei *et al.,* [13]	MgO- WCNTs/ ethylene glycol	Increasing volume and decreasing temperature led to thermal conductivity improvement.
Afrand [95]	MgO-FMWCNT/ EG	The improvement of thermal conductivity is happened by the cluster formation in liquid.
Shahsavar *et al.,* [96]	Fe_3O_4 –CNT/ water	Thermal conductivity is dependent on the ultrasonic period.
Abbasi *et al.,* [97]	MWCNT-ɣ-Al_2O_3/ water	Thermal conductivity is affected by the nanofluid's stability.
Ahmadi *et al.,* [98]	Al_2O_3/ water	The thermal conductivity improves with rising temperature and solid volume fraction of nanoparticles.
Hamid *et al.,* [99]	TiO_2-SiO_2 (20:80, 40:60, 50:50, 60:40 and 80:20)/ Water-EG	The thermal conductivity increases with the increasing volume concentration and temperature.
Esfe *et al.,* [14]	MWCNT-SiO_2 (30:70%)/ EG	The thermal conductivity improves with growing volume concentration and temperature.
Asadi *et al.,* [100]	Al_2O_3-MWCNT/ Thermal oil	Thermal conductivity is improved with the enhanced temperature and concentration of nanoparticles.
Zadkhast *et al.,* [101]	MWCNT-CuO/ Water	Rising temperature and solid volume fraction can enhance the thermal conductivity of nanofluid.
Nabil *et al.,* [28]	TiO_2-SiO_2/ water-EG(60:40)	The thermal conductivity increases with increasing volume concentration and temperature.
Xu *et al.,* [102]	Al_2O_3/water	Thermal conductivity improves with increasing solid concentration.

Table 3
Summary of the relationship equation of the thermal conductivity of various nanofluids

Authors	Nanofluids	Equations
Sundar *et al.,* [87]	ND-Fe_3O_4/water; EG-water (20:80), (40:60), (60:40)	$\frac{K_{nf}}{K_{bf}}$= a + b$\o$ T= 20°C; $\frac{K_{nf}}{K_{bf}}$= 1.0149 + 0.2403$\o$ T= 30°C; $\frac{K_{nf}}{K_{bf}}$= 1.0188 + 0.3751$\o$ T= 40°C; $\frac{K_{nf}}{K_{bf}}$= 1.0157 + 0.4728$\o$ T= 50°C; $\frac{K_{nf}}{K_{bf}}$= 1.0168 + 0.5697$\o$ T= 60°C; $\frac{K_{nf}}{K_{bf}}$= 1.0150+ 0.6818$\o$
Esfe *et al.,* [88]	SWCNT-MgO (20:80)/ Ethylene glycol	$\frac{K_{nf}}{K_{bf}} = 0.90844 - 0.06613\o^{0.3}T^{0.7} + 0.01266\o^{0.31}T$
Sundar *et al.,* [92]	ND-Co_3O_4/water; EG; EG-water ((20:80), (40:60), (60: 40)	$\frac{K_{nf}}{K_{bf}} = 0.9978\ (1 + \ \o^{0.6556})$
Vafaei *et al.,* [13]	MgO-MWCNTs/ ethylene glycol	$\frac{K_{nf}}{K_{bf}} = 0.9787 + \exp\ (\ 0.3081\o^{0.3097} - 0.002T)$
Afrand [95]	MgO-FMWCNT/ EG	$\frac{K_{nf}}{K_{bf}} = 0.8341 + 1.1\o^{0.243}T^{0.289}$
Asadi *et al.,* [100]	Al_2O_3-MWCNT/ Thermal oil	$K_{nf} = 0.1534 + (0.00026)T + 1.1193\o$
Zadkhast *et al.,* [101]	MWCNT-CuO/ Water	$\frac{K_{nf}}{K_{bf}} = 0.907 \exp(\ 0.36\ \o^{0.3111} + 0.00095T)$
Nabil *et al.,* [28]	TiO_2-SiO_2/ water-EG(60:40)	$\frac{K_{nf}}{K_{bf}} = \left(1 + \frac{\o}{100}\right)^{5.5} \left(\frac{T}{80}\right)^{0.01}$

4.2 Viscosity

Viscosity is termed as the magnitude of fluid's resistance to flow or internal friction of a fluid. A fluid's property significantly affects the pumping power, pressure drop, and convective heat transfer properties in fluid flow. Suresh *et al.,* [105] experimented using hybrid nanofluids Al_2O_3 - Cu/water at 32°C for volume concentration from 0.1 to 2.0%. The scientists observed that viscosity is unconstrained to shear rate indicating hybrid nanofluids' Newtonian conduct and viscosity enhances with an increase in nanoparticles' concentration owing to cluster formation, sedimentation and surface adsorption expanding the hydrokinetic distance across nanoparticles. Similarly, Esfe *et al.,* [51] also concluded that the value of dynamic viscosity grows up with the enhanced concentration of nanoparticles while studying Ag-MgO/ water hybrid nanofluids at 0.5-2.0% volume concentrations. Finally, they presented an equation (Eq. (9)) for water-based Ag-MgO nanofluids' viscosity concerning only nanoparticles concentration.

$$\mu_{nf} = \mu_{bf}\,(1+32.795\o - 7214\o^2 + 714{,}600\o^3 - 0.1941 * 10^8\o^4) \tag{9}$$

Later in 2016, Esfe *et al.,* [106] investigated the impact of concentration and temperature of solid particles on the viscosity of MWCNTs-SiO_2 (20:80) hybrid nanofluids. This study is performed using SAE 40 as a base liquid at different concentrations of nanoparticles and different temperatures. The tests uncovered the Newtonian conduct of SAE-based MWCNTs-SiO_2 at the concentration till 1.0% and the non-Newtonian conduct at 1.5% and 2.0% concentrations, respectively. The authors then proposed a relationship with a maximum error of 1.2%, which is presented in Eq. (10).

$$\mu_{nf} = \mu_{bf}(a_0 + a_1\emptyset + a_2\emptyset^2 + a_3\emptyset^3) \tag{10}$$

where a_0, a_1, a_2, a_3 are constants, which are presented in Table 6.

Bahrami *et al.,* [107] also discovered the behaviour of viscosity depending on concentration and temperature of particles using EG-Water (80:20) based Fe-CuO hybrid nanofluids for different concentrations (0.05 to 1.5%) and temperatures (25°C to 50°C) and found that viscosity enhanced for higher nanoparticles concentration and delineated for lower temperature. The study uncovered that samples with lower concentrations showed Newtonian behaviour while the samples with comparatively high concentration showed non-Newtonian behaviour, which was not dependent on temperature. They also found that the consistency and power-law index through curve-fitting using exploratory findings demonstrate non-Newtonian behaviour for high concentration. Asadi *et al.,* [108] demonstrated the Newtonian behaviour of MWCNTs-MgO (20:80)/motor oil (SAE 40) from 25°C to 50°C. The experimental findings had shown that the viscosity increments with expanding concentration of particles and diminish with rising temperature and finally, a new equation (Eq. (11)) for gauging the viscosity of SAE based MWCNTs-MgO nanofluid depending on trial information allowing a maximum 8% error, was presented.

$$\mu_{nf} = 328{,}201T^{-2.053}\emptyset^{0.09359} \tag{11}$$

Increasing the volume fraction of particles has an essential influence on the enhancement of viscosity [100]. Asadi *et al.,* [100] experimented with Al_2O_3-MWCNT/thermal oil to assess the heat transfer efficiency for 0.125 to 1.5% concentration of particles. The increase in the amount of MWCNT in the base fluids increases the probability of nano-cluster formation, which retards the smooth movement of oil layers by increasing viscosity. In contrast, a decreasing trend of dynamic viscosity is found for increasing temperature due to debilitating the connection among molecules. In this study, the maximum increase is derived at 40°C for all considered concentrations, and at 1.5% solid concentration, the maximum increase of dynamic viscosity (81%) is found for all considered temperatures, whereas at 50°C minimum increase is found for all studied concentration except 0.5% and 1%. Finally, researchers proposed new correlations for a selected range of concentrations and temperature with high validity and the relationships are presented in Eq. (12)-(17).

$$T = 25°C,\ \mu_{nf} = 417.71 + 76.566\emptyset \tag{12}$$

$$T = 30°C,\ \mu_{nf} = 280.79 + 69.027\emptyset \tag{13}$$

$$T = 35°C,\ \mu_{nf} = 207.9 + 54.585\emptyset \tag{14}$$

$$T = 40°C,\ \mu_{nf} = 158.3 + 39.5\emptyset \tag{15}$$

$$T = 45°C,\ \mu_{nf} = 124.29 + 20.952\emptyset \tag{16}$$

$$T = 50°C,\ \mu_{nf} = 93.602 + 20.372\emptyset \tag{17}$$

Alrashed *et al.,* [109] also recommends that the enhancement of weight percentage of nanoparticles, density and viscosity of working fluid increases resulting in the pressure drop more critical. During the investigation of behaviour and heat transfer properties of 0.5% carboxymethyl cellulose (CMC)/water-based alumina nanofluid, the volumetric concentration of alumina nanoparticles was 0.5 and 1.5 [110]. Heat transfer properties can be enhanced with the rising volume concentration and decreasing diameter of nanoparticles while dynamic viscosity and density can be improved with the increasing volume fraction of alumina. However, Nabil *et al.,* [28] examined the thermophysical behaviour of TiO_2-SiO_2 (50:50)/water-EG (60:40) nanofluid for various concentrations and temperatures. In their experiment, the KD2 Pro Thermal Properties Analyser and Brookfield LVDV III Ultra rheometer were used to measure thermal conductivity and viscosity. Maximum 62.5% increment of average relative viscosity was found at 3% volume concentration while minimum 25.9% viscosity was found at 0.5% concentration and Newtonian behaviour of fluid was observed up to 3% volume concentration. The study revealed that the viscosity of TiO_2-SiO_2 /water-EG nanofluid increases with rising solid concentration. Besides, viscosity decreases with rising temperature because of weakening the intermolecular interactions among molecules with rising temperature [28,53,111]. Nabil *et al.,* [28] proposed a correlation (Eq. (18)) for relative viscosity with reasonable accuracy, valid up to 3% volume concentration for temperature ranging from 30 to 70°C.

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 37\left(0.1 + \frac{\varnothing}{100}\right)^{1.59}\left(0.1 + \frac{T}{80}\right)^{0.31} \tag{18}$$

In the interim, the viscosity of TiO_2-SiO_2 nanofluids increments with expanding solid particles' concentration and diminishes with expanding temperature pursuing the base liquid pattern [41]. Similarly, Ho *et al.,* [112] also mentioned that viscosity likewise enhanced by increasing nanoparticle concentrations, which builds up pressure drop more in micro-channel and requires comparatively more pumping power.

With a constant volume concentration of 1%and under three different working temperatures of 30, 50 and 70°C the investigation of heat transfer performance of different mixture ratios of TiO_2-SiO_2 (20:80, 40:60, 50:50, 60:40 and 80:20) nanofluid is conducted by Hamid *et al.,* [47] while using water/EG as a base fluid. Under the turbulent region, the study is directed with Reynolds number from 3000 to 24,000. However, mixture ratios of 20:80 and 40:60 of TiO_2-SiO_2 nanofluids are suggested to use for heat transfer performance from this study because of better thermal conductivity and viscosity. Moreover, the 80:20 ratio shows the lowest viscosity, and the 50:50 ratio shows the maximum viscosity due to particles arrangement. Nguyen *et al.,* [111] and Esfe *et al.,* [113] featured that the liquid inside shear pressure is more prominent at high concentration of solid particles while the augmentation of the temperature debilitated the intermolecular association. During contemplating the rheological behaviour of MWCNTs – ZnO hybrid nanofluids using motor oil (SAE 40) as base fluid, estimations were performed at temperatures from 25 to 60°C for volume concentrations extending from 0.05% to 1.0% and reasoned that the viscosity diminishes as the temperature and concentration of particles increase showing Newtonian behaviour of hybrid nanofluids [113]. Finally, for viscosity estimation, a correlation equation is proposed with a most extreme deviation of ± 2:0%, and it is expressed in Eq. (19).

$$\mu_{nf} = \mu_{bf}(A + B\varnothing + C\varnothing^2 + D\varnothing^3) \tag{19}$$

where A, B and C are constants.

Esfe *et al.,* [114] carried out an experiment to explore the variations of viscosity MWCNT-TiO_2 (20% -80%) / Water-EG (70% -30%) hybrid nanofluids in the range of 0.05 to 0.85% volume concentration at 10, 30 and 50°C. Maximum 83% of viscosity is found at 10°C and 0.85% volume concentration. Newtonian conduct of water-EG based MWCNT-TiO_2 hybrid nanofluids is found at 0.05 and 0.45% volume concentrations, whereas at 0.85%, almost non-Newtonian behaviour are revealed. The authors also conclude that the alteration of the value of viscosity with concentration is bigger for less temperature because the atomic obligations of the particles and base liquid are redeemed, and the liquid layers move effectively on one another with rising concentration. Besides, with the rising of volume concentration, viscosity also increases due to the increment of nanoparticles collisions, but at 50°C, viscosity is not affected by volume fraction. Finally, performing curve-fitting on the data of viscosity a new correlation (Eq. (20)) is introduced with the R^2 value of 0.9913.

$$\mu_{nf} = 6.35 + 2.56ø - 0.24T - 0.068øT + 0.905ø^2 + 0.0027T^2 \qquad (20)$$

Maximum, 320% viscosity, is derived from the experiment at 0.73% volume concentration at 25°C during exploration of viscosity variability of single-wall carbon nanotube (SWCNT)–water nanofluid using equilibrium molecular dynamics (MD) simulation [57]. Like other previous investigations, this study reports viscosity enhancement with a rising concentration of nanoparticles and lowering the nanofluid temperature. Besides, through comparison of MD solution results with Einstein, Brinkman and Batchelor models (Eq. (21)-(23)) [115-117], it is evident that none of the traditional models can appraise the dynamic viscosity of nanofluid. Because these models are liable to the material, volume concentration and shape of nanoparticles and the current model temperature of nanofluid are excluded.

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5ø \text{ ; Einstein Model} \qquad (21)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{(1-ø)^{2.5}} \text{ ; Brinkman Modified Einstein Model} \qquad (22)$$

$$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5ø + 6.5ø^2 \text{ ; Batchelor Model} \qquad (23)$$

MXene/silicone oil nanofluid showed that viscosity was decreased by 37% when the temperature was raised from 25°C to 50°C [104]. In another study, the viscosity of TiO_2-Al_2O_3 hybrid nanofluids showed 56.64% enhancement at volume concentration of 0.02% and 30°C compared to base fluid [60]. Table 4 and Table 5 present the experimental results and responsible reasons for enhancement /deterioration in viscosity of nanofluids studied in recent years. The reviewed investigations show that viscosity is related to the solid volume fraction of nanoparticles, temperatures, intermolecular forces among nanoparticles, and between nanoparticles and base fluids. Table 6 summarises the correlations for measuring the viscosities of different types of nanofluids, which is applicable for a specific type of nanofluids, sometimes for particular temperatures and specific mixture ratios.

Table 4
Summary of exploratory results of the viscosity of different nanofluids

Reference	Nanofluids	Rheology & Other Relevant Information	Changes of Viscosity (%)
Suresh *et al.,* [105]	Al_2O_3-Cu/ water	0.1 < ø ≤ 2%; Room temperature 32°C	115% improvement at 2.0% vol con. and at 32°C.
Bahrami *et al.,* [107]	Fe-CuO/ EG-water	0.05 < ø ≤ 1.5% 25°C ≤ T ≤ 50°C; Both Newtonian and non-Newtonian	1.090% improvement at 1.5 vol% and 25°C.
Asadi *et al.,* [108]	MWCNTs -MgO/SAE 40	0.0025 < ø ≤ 0.02% 25°C ≤ T ≤ 50°C; Newtonian	65% increment at 2.0 wt% and 40°C.
Asadi *et al.,* [100]	Al_2O_3-MWCNT/ Thermal oil	0.125 < ø ≤ 1.5% 25°C ≤ T ≤ 50°C; Newtonian	Max. 81% enhancement at 1.5% vol% for all considered temp; Min increase at 50°C.
Nabil *et al.,* [28]	TiO_2-SiO_2/ water:EG (60:40	0.05 < ø ≤ 3% 30°C ≤ T ≤ 80°C; Newtonian	Max. 62.5% increment at 3% vol. con. and min. 25.9% at 0.5% vol. con.
Hamid *et al.,* [99]	TiO_2-SiO_2 (20:80, 40:60, 50:50, 60:40 and 80:20)/ Water-EG	ø = 1%; 30^0 C ≤ T ≤ 70°C; Newtonian	Max. increment at 50:50 ratio and min at 80:20 ratio of nanoparticles.
Esfe *et al.,* [51]	Ag-MgO/water	0.5 < ø ≤ 2 %	24% improvement at 2.0% vol con.
Esfe *et al.,* [106]	MWCNTs-SiO_2 (20:80)/ SAE 40	0.00625 < ø ≤ 2% 25°C ≤ T ≤ 50°C; Both Newtonian and non-Newtonian	30:2% enhancement at 1.0 vol% and 40°C.
Esfe *et al.,* [113]	MWCNTs-ZnO/SAE 40	0.05 < ø ≤ 1% 25°C ≤ T ≤ 60°C; Newtonian	33.3% improvement at 1.0 vol% and 40°C.
Esfe *et al.,* [114]	MWCNT-TiO_2 (20% - 80%)/water-EG (70% -30%)	0.05 < ø ≤ 0.85% 10°C ≤ T ≤ 50°C; Both Newtonian and non-Newtonian	83% enhancement at 0.85% vol. con. and at 10°C.
Jabbari *et al.,* [57]	SWCNT/ water	0.125 < ø ≤ 0.734% 25°C ≤ T ≤ 65°C	320% improvement at 0.73% vol. con. at 25°C.

Table 5
Summary of responsible reasons behind the adjustment of the viscosity of nanofluids

Reference	Nanofluids	Reasons
Suresh *et al.,* [105]	Al_2O_3-Cu/ water	Viscosity increases with the enhancement of nanoparticles' volume concentration, cluster formation and surface adsorption increasing nanoparticles' hydrodynamic diameter.
Bahrami *et al.,* [107]	Fe-CuO/ EG-water	Viscosity increases due to rising nanoparticles concentration through cluster formation for van der Waals forces among particles and decreases with increasing shear rate and increasing temperature.
Asadi *et al.,* [108]	MWCNTs -MgO/SAE 40	Increment and deterioration of viscosity are due to expanding concentration of solid particles and growing temperature, respectively.
Asadi *et al.,* [100]	Al_2O_3-MWCNT/ Thermal oil	Viscosity increases with increasing solid concentration of particles due to the increasing probability of nano-cluster formation and deteriorates with increasing temperature for weakening the interaction among particles.
Nabil *et al.,* [28]	TiO_2-SiO_2/ water:EG (60:40	Viscosity increases with rising volume concentration and drops with growing temperature because of weakening the molecules' intermolecular attraction with rising temperature.
Hamid *et al.,* [99]	TiO_2-SiO_2 (20:80, 40:60, 50:50, 60:40 and 80:20)/ Water-EG	Viscosity depends on the distribution of the particles and decreases with increasing temperature.
Esfe *et al.,* [113]	MWCNTs-ZnO/SAE 40	Viscosity diminishes and increments for expanding temperature and concentration of particles, respectively.
Esfe *et al.,* [114]	MWCNT-TiO_2 (20% - 80%)/water-EG (70% -30%)	Viscosity increases with the increment of nanoparticles collisions and decreases with rising temperature for redeeming nanoparticles' intermolecular bond.
Jabbari *et al.,* [57]	SWCNT/ water	Viscosity enhances with rising concentration and lowering the temperature of nanofluid.

5. Challenges, Problems, Opportunity

Numerous researchers report that higher thermal conductivity can be derived from a higher concentration of nanoparticles. On the other hand, agglomeration of particles may reduce heat transfer performance by retarding fluid motion. Besides, increasing the concentration of particles is also associated with the higher or abnormal increment of viscosity. Perhaps, it may also lead to instability, erosion or corrosion of interfacing surfaces. So, it can be summarised nanoparticles have the pertinent concentration for a specific type of nanofluids. Future research can focus on the optimum concentration or the concentration limit to get higher thermal conductivity with optimum viscosity and proper stability, addressing nanofluids' corrosion and erosion characteristics. Before commercializing the nanofluids, the issues of agglomeration and sedimentation should be resolved because prolonged durability should be the most intensely focused research objective for this purpose. Most of the findings reveal that viscosity improves with the rising concentration of nanoparticles due to an increased probability of cluster formation, increasing hydrodynamic diameter through surface adsorption, particles' distribution and collisions. On the contrary, viscosity declined with increasing nanofluid temperature due to enervating the attraction forces among nanoparticles and increasing shear rate. The maximum increment of viscosity is found for SWCNT/water nanofluid [57]. Some researchers also report high carbon nanotube viscosity, and alumina contained nanofluid [100,105,108,114]. This high viscosity may retard their industrial applications.

During the investigation of nanofluids' thermal properties, the volume concentration of particles is mostly considered parameters while the usually considered temperature range is from 20°C to 80°C, which is inadequate for measuring the performance of nanofluids at low and high temperatures in industries. The estimation of nanofluids' thermophysical properties at lower and higher temperatures could be invaluable to recognize upper and low-temperature applications of nanofluids in the practical field. So, the range of temperature may be enlarged in future studies. Moreover, most of the researchers failed to anticipate the estimation of nanofluids' thermophysical characteristics from the comparison between experimental results and different published models except in very few cases [115-118]. So, there is no all-inclusive model to precisely appraise the thermal conductivity and viscosity of nanofluids. Thus, different types of correlations are proposed by various researchers to predict thermophysical properties for different conditions. Another critical issue of nanofluid is its high production cost. Future studies on nanoparticles' production methods may help innovate cost-effective and economic processes for producing on a large scale.

Table 6
Summary of various relationships for the viscosity of nanofluids

Authors	Information	Equations
Esfe *et al.,* [51]	Ag-MgO/water $0.5 < \o \le 2\%$	$\mu_{nf} = \mu_{bf}(1+32.795\o - 7214\o^2 + 714{,}600\o^3 - 0.1941 * 10^8\o^4)$
Esfe *et al.,* [106]	MWCNTs-SiO_2 (20:80)/ SAE 40 $0.00625 < \o \le 2\%$ $25°C \le T \le 50°C$	T= 25°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0343 + 0.2336\o - 0.2604\o^2 + 0.2375\o^3$ T= 30°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0435 + 0.4417\o - 0.5087\o^2 + 0.2985\o^3$ T= 35°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0202 + 0.7748\o - 1.2154\o^2 + 0.7073\o^3$ T= 40°C: $\frac{\mu_{nf}}{\mu_{bf}} = 0.9903 + 1.0245\o - 1.7095\o^2 + 0.9978\o^3$ T= 45°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0279 + 0.7283\o - 1.0703\o^2 + 0.6115\o^3$ T= 50°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0347 + 0.6317\o - 1.0729\o^2 + 0.6942\o^3$
Asadi *et al.,* [108]	MWCNTs -MgO/SAE 40 $0.0025 < \o \le 0.02\%$ $25°C \le T \le 50°C$	$\mu_{nf} = 328{,}201 T^{-2.053} \o^{0.09359}$
Nabil *et al.,* [28]	TiO_2-SiO_2(50:50)/water-EG (60:40) $0.5 < \o \le 3\%$ $30°C \le T \le 80°C$	$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 37\left(0.1 + \frac{\o}{100}\right)^{1.59}\left(0.1 + \frac{T}{80}\right)^{0.31}$
Esfe *et al.,* [113]	MWCNTs-ZnO/SAE 40 $0.05 < \o \le 1\%$ $25°C \le T \le 60°C$	$\mu_{nf} = \mu_{bf}(A + B\o + C\o^2 + D\o^3)$ T= 25°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0087 + 0.1553\o - 0.033\o^2 + 0.0631\o^3$ T= 30°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0085 + 0.2499\o - 0.2865\o^2 + 0.2043\o^3$ T= 35°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0223 + 0.5341\o - 0.6313\o^2 + 0.366\o^3$ T= 40°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0382 + 0.5376\o - 0.5013\o^2 + 0.261\o^3$ T= 45°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.013 + 0.6448\o - 0.9427\o^2 + 0.5225\o^3$ T= 50°C: $\frac{\mu_{nf}}{\mu_{bf}} = 1.0132 + 0.6596\o - 0.913\o^2 + 0.4822\o^3$
Asadi *et al.,* [100]	Al_2O_3-MWCNT $0.125 < \o \le 1.5\%$ $25°C \le T \le 50°C$	T= 25°C: $\mu_{nf} = 417.71 + 76.566\o$ T= 30°C: $\mu_{nf} = 280.79 + 69.027\o$ T= 35°C: $\mu_{nf} = 207.9 + 54.585\o$ T= 40°C: $\mu_{nf} = 158.3 + 39.5\o$ T= 45°C: $\mu_{nf} = 124.29 + 20.952\o$ T= 50°C: $\mu_{nf} = 93.602 + 20.372\o$
Esfe *et al.,* [114]	MWCNT-TiO_2 (20% -80%) / Water-EG (70% -30%)	$\mu_{nf} = 6.35 + 2.56\o - 0.24T - 0.068\o T + 0.905\o^2 + 0.0027T^2$

6. Conclusion

The paper describes a comprehensive, critical review of nanofluids' various types, preparation method, their thermophysical properties (thermal conductivity, viscosity) of nanofluids. Many researchers investigated nanofluids' preparation method while the two-stage method is highly recommended and employed the method. For this paper, viscosity and thermal conductivity are selected as thermophysical properties to review because most experimental studies are centred on viscosity and thermal conductivity concerning nanofluids' thermophysical attributes. Achieving more stable nanofluids with more excellent thermal conductivity and lower viscosity is research anticipation, and it has been explored for the last couple of decades. However, thermal conductivity is the most examined parameter among all thermophysical properties of nanofluids. Most of the research groups uncovered that nanofluids exhibit improved thermal conductivity and viscosity with increasing the solid concentration of particles except few exemptions. Moreover, the type of base fluids and particles, the synthesis method and mixture ratio of particles, stability, temperature, and ultrasonic period significantly influence nanofluids' thermal conductivity. Among reviewed literature, maximum thermal conductivity is reported as 300% for kerosene-based oleic acid-coated Fe_3O_4 nanofluids with the inclusion of a magnetic field. Viscosity which is another valuable thermal property of nanofluids, affects the heat transfer applications substantially. From reviewed most recent literature, 320% of the highest viscosity enhancement is achieved from single-walled carbon nanotube containing water-based nanofluid at 0.73% concentration. However, most researchers conclude that the value of viscosity can be prompt with a rising concentration of particles and declined with increasing temperature. The study also reveals that nanofluids show both rheological behaviours of non-Newtonian and Newtonian. Despite showing many novel properties, there is comparatively very few research on using nanofluids in industries. Recently, the field of nanofluids has been pulling in specialists' attention. So, it is expected to achieve an increasing number of researches on the applications of nanofluids in machining and overall industries and also focusing thermophysical properties such as viscosity, density, specific heat as well as thermal conductivity considering the shape and other dimensions of nanoparticles, synthesis of nanofluids, surfactant type, pH, mixing ratio and time as well as ultrasonication time of nanofluids. Hence, applications of nanofluids can impact substantially as heat transfer fluids in nanotechnology practically. Finally, this article can be utilised to build innovative nanofluids with improved thermophysical properties for efficient thermal engineering applications. In order to obtain more promising and practical results, large-scale experimentation and comparative investigation of various advanced nanofluids in practical fields are required than just laboratory-scale experiments.

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