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A review on hybrid nanofluids for engineering applications

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ABSTRACT

Nanofluids have found crucial presence in heat transfer of applications with their promising characteristics that can be controlled as per requirements. In the present paper a critical review of Nanofluids has been carried out for the past two decades to design a new hybrid nanofluids for various engineering applications. Mono nanofluids, prepared with a single kind of nanoparticles, possess certain specific benefits owing to the properties of the suspended nanoparticle. However to further improve the characteristics of nanofluids, that could possess a number of favourable characteristics, researchers developed a new generation heat transfer fluid called hybrid nanofluid. Hybrid nanofluids are prepared either by dispersing dissimilar nanoparticles as individual constituents or by dispersing nanocomposite particles in the base fluid. Hybrid nanofluids may possess better thermal network and rheological properties due to synergistic effect. Hybrid nanofluids though having thermal performance properties but as a new type of working fluids, there are some challenges in their development. Firstly, there is lack of agreement between results obtained by different researchers; secondly, there is lack of theoretical model that can predict the exact behaviour of the hybrid nanofluids. Thirdly, in the preparation method, different methods lead to different result for a given nanofluid and volume fraction. Many researchers have used TiO_2 & SiC as nano additives for increasing the performance of machining operation. In the present paper a new class of hybrid nano fluid i.e. SiC and TiO_2 is proposed to study using proper combinations, necessity and benefits of implementing the performance of machining operations.

1. Introduction

Hybrid nanofluid is a new class of nanofluids engineered by dispersing two different nanoparticles into conventional heat transfer fluid. Hybrid nanofluids are potential fluids that offer better heat transfer performance and thermo-physical properties than convectional heat transfer fluids (oil, water and ethylene glycol) and nanofluids with single nanoparticles. Scientific findings have indicated that hybrid nanofluid can replace single nanofluid since it provides more heat transfer enhancement especially in the areas of automobile, electro-mechanical, manufacturing process, HVAC and solar energy. In this paper, summarized the recent progress related to the preparation methods of hybrid nanofluids, factors affecting their stability, methods of enhancing thermal properties and current applications of hybrid nanofluids.

Hybrid nanofluids are the new class innovative heat transfer fluids, which are still in developing stage and extensive research has to be carried out to bring them to commercial scale. Thorough understanding of the synthesis, characterization and thermo physical properties of hybrid nanofluid are essential to use them in the domestic and industrial applications. Research done so far on hybrid nanofluids is very limited and systematic experimental investigations needs to be carried out to estimate the thermo physical and the hydrodynamic behaviour to use them for specific engineering applications.

2. Review of literature

A compressive year wise literature survey has been carried out to in the field of hybrid nano-fluids, to understand the present scenario, Preparation, Stability Mechanisms, and Applications of nanofluids.

Suresh et al. [1] synthesized Al_2O_3–Cu hybrid particles by hydrogen reduction technique from the powder mixture of Al_2O_3

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and Cu. A 90:10 wt proportions obtained from a chemical route synthesis. Al_2O_3 –Cu/water hybrid nanofluids with volume concentrations from 0.1% to 2% (0.1%, 0.33%, 0.75%, 1%, 2%) were then prepared in two step method with sodium lauryl sulphate (SLS) as a dispersant by using an ultrasonic vibrator by dispersing the synthesized nanocomposites powder in deionised water.

The thermal conductivity and viscosity of the nanofluids were measured using an instrument, KD2-Pro thermal analyzer and Brookfield cone and plate viscometer respectively. The experimental results show that there is a significant enhancement in effective thermal conductivity of the prepared hybrid nanofluids compared with deionised water. It has also been observed that the thermal conductivity of nanofluids increases remarkably with increasing volume fraction of nanoparticles.

Viscosity measurements indicate that Al_2O_3 –Cu/water nanofluids behave as Newtonian fluids. The viscosity values for hybrid fluids are higher when compared to the viscosity of alumina/water nanofluids. The experimental results have been compared with predictions by the existing theoretical models. It has been found that the experimental results are significantly higher than those predicted by existing models for solid–liquid mixtures.

Robert Taylori et al. [2] conducted a critical review of first decade of Nano fluid which is focused on the measuring and modeling fundamental thermo physical properties of nanofluids (thermal conductivity, density, viscosity, convection coefficients). Recent research, however, has started to highlight how nanofluids might perform in a wide variety of other applications. These applications range from their use in Nano medicine to their use as solar energy harvesting media. Overall, this review summarizes the novel applications and uses of nanofluids while setting the stage for future Nano fluid use in industry.

Wei Yu et al. [3] summarizes the recent developments in the study of nanofluids, including the preparation methods, the evaluation methods for their stability, ways to enhance their stability, stability mechanisms, and their potential applications in heat transfer intensification, mass transfer enhancement, energy fields, mechanical fields, biomedical fields, and so forth

The detailed and accurate structure characterizations of the suspensions may be the key to explain the discrepancy in the experimental data. Secondly, increase in viscosity by the use of nanofluids is an important drawback due to the associated increase in pumping power. The applications for nanofluids with low viscosity and high conductivity are promising. Enhancing the compatibility between nano materials and the base fluids through modifying the interface properties of two phases may be one of the solution routes. Thirdly, the shape of the additives in nanofluids is very important for the properties; therefore, the new nanofluid synthesis approaches with controllable microscope structure will be an interesting research work. Fourthly, stability of the suspension is a crucial issue for both scientific research and practical applications. The stability of nanofluids, especially the long term stability, the stability in the practical conditions, and the stability after thousands of thermal cycles should be paid more attention. Fifthly, there is a lack of investigation of the thermal performance of nanofluids at high temperatures, which may widen the possible application areas of nanofluids, like in high-temperature solar energy absorption and high-temperature energy storage. The concept of nanofluids is extended by the use of phase change materials, which goes well beyond simply increasing the thermal conductivity of a fluid. It is found that the indium/polyalphaolefin phase change nanofluid exhibits simultaneously enhanced thermal conductivity and specific heat

Saloumeh Mesgari et al. [4] focused on the synthesis of a nanohybrid of multi-walled carbon nanotubes (MWCNTs) and gamma alumina (g-Al_2O_3) particles. In this study, functionalized CNTs were synthesised via a solvothermal process with various concentrations of carboxylic acid groups (–COOH). The microstructure of the synthesised Nano hybrids was characterized via high-resolution transmission electron microscopy (HRTEM), transmission electron microscopy (TEM), and energy-dispersive X-ray spectroscopy (EDX). The MWCNT/g-Al_2O_3 nanofluid was prepared using a two-step method. The thermal conductivities of different Nano hybrids were measured with a KD2-Pro thermal analyzer. The zeta potential and particle size distribution were determined to investigate the stability of the nanofluid. The results showed that the functional groups had a significant influence on the thermal conductivity of the hybrid nanofluid. The data showed that the enhancement in thermal conductivity reached up to 20.68% at a 0.1% volume fraction of hybrid, for a gum arabic (GA) based nanofluid.

Azadeh Ghadimi et al. [5] investigated the stability of titania nano-suspensions by comparing the effect of surfactant addition and ultrasonic processing. Six different nanofluids with 0.1 wt% loading of TiO_2 nanoparticles (25 nm diameter) were prepared using a two-step method. Ultrasonic processing (i.e. bath and horn) were applied to help the homogeneity and Sodium Dodecyl Sulfate (SDS) as anionic surfactant was added to monitor the stability of the samples. UV–vis spectrometry, particle size distribution, zeta potential, Transmission Electron Microscopy (TEM) and sedimentation photo capturing were applied to visualize the stability and sedimentation rate of the prepared nanofluids. In addition, thermal conductivity and viscosity of these six samples were measured. The optimized nanofluid was selected in terms of better stability, thermal conductivity and viscosity. The results revealed that 3-h ultrasonic bath process with the addition of 0.1 wt% of surfactant can be the most stable suspension with the highest thermal conductivity for further applications within 1 month.

Munkhbayar et al. [6] demonstrated an improvement in the thermal conductivity of TiO_2-water nanofluids by the addition of the flattened Ag structures. The surface/shape of the synthesized Ag nanoparticles was changed to be flattened by planetary ball milling. Then, to enhance the thermal conductivity of TiO_2 nanofluids, the flattened "Ag" particles are incorporated with the combination of small (15 nm) and large (300 nm) TiO_2 nanoparticles in an aqueous solution. The thermal conductivities of Ag/TiO_2–water nanofluids with various weight concentrations are measured at temperatures ranging from 15 to 40 °C. As a result, the present study confirms that the thermal conductivity of TiO_2 based solution can be improved by introducing the flattened "Ag" particles.

Madhesha et al. [7] has been carried out experimental study to investigate the heat transfer potential and rheological characteristics of copper–titania hybrid nanofluids (HyNF) using a tube in the tube type counter flow heat exchanger. The nanofluids were prepared by dispersing the surface functionalized and crystalline copper–titania hybrid Nano composite (Hy NC) in the base fluid, with volume concentrations ranging from 0.1% to 2.0%. The Heat transfer and rheological characteristics of nanofluids containing Hy NC of an averaged size of 55 nm were experimentally investigated. The test results reveal that the convective heat transfer coefficient, Nusselt number and overall heat transfer coefficient were increased by 52%, 49% and 68% respectively, up to 1.0% volume concentration of Hy NC. Beyond the volume concentration of 1.0% and up to 2.0%, the reduction in the convective heat transfer potential and the Nusselt number were marginal, which signified the effective thermal conductivity enhancement in Hy NF. Thus, the new correlation can be helpful in predicting the heat transfer potential for the specific volume concentration of Hy NF.

Jahar Sarkarn et al. [8] summarizes recent researches on synthesis, thermo physical properties, heat transfer and pressure drop characteristics, possible applications and challenges of hybrid nanofluids. Review showed that proper hybridization may make the hybrid nanofluids very promising for heat transfer enhancement, however, lot of research works is still needed in the fields of preparation and stability, characterization and applications to overcome the challenges.

Parameshwarana et al. [9] presents the experimental investigation on the thermal properties and viscosity of the new organic phase change material embedded with the silver–titania hybrid Nano composite (Hy NP CM) with the mass proportions ranging from 0.1% to 1.5%. The Hy NP CM embedded with the surface functionalized hybrid Nano composite exhibited improved thermal conductivity. Experimental results reveal that, the freezing and the melting times of the Hy NP CM were reduced by 23.9% and 8.5% respectively, when compared to the pure PCM. The increased mass proportion of Hy NC resulted in the increased viscosity up to 3.89%, which suggests the existence of relative dependencies between the thermal properties and the viscosity of the Hy NP CM.

Zhuowei Liua et al. [10] proposed a new method that coupling TiO_2 nanoparticles on ZrP Nano platelets for improving the stability of TiO_2 suspensions, which is differ from the traditional methods of adding various surfactants. Comparing 50 days long term stability of three samples, which are TiO_2 suspensions, mixture of TiO_2 and exfoliated ZrP suspensions, exfoliated TiO_2/ZrP couples suspensions, the results show that the stability of exfoliated TiO_2/ZrP couples suspensions is the best and it could keep 62% of initial concentration on the 50th day. TiO_2 nanoparticles could not aggregate into bigger particles as they are loaded on the surface of nanoplatelets is the main reason for improving stability, and the viscosity of exfoliated TiO_2/ZrP couples suspensions are much higher than TiO_2 suspensions.

Saeed et al. [11] experimented study on the thermal conductivity of f-MWCNTs–Fe_3O_4/EG hybrid nanofluids in temperature ranging from 25 °C to 50 °C for various samples of nanofluids with solid volume fractions of 0.1%, 0.25%, 0.45%, 0.8%, 1.25%, 1.8% and 2.3% was examined. Experimental finding revealed that the thermal conductivity enhances with increasing the solid volume fraction and temperature. Results also showed that, at higher temperatures, the variation of thermal conductivity ratio with solid volume fraction was more than that at lower temperatures. Furthermore, the effect of temperature on the thermal conductivity ratio was more noticeable at higher solid volume fractions. The maximum enhancement of thermal conductivity of nanofluid was 30%, occurring at the temperature of 50 °C and the solid volume fraction of 2.3%. Finally, in order to predict the thermal conductivity ratio of f-MWCNTs/EG hybrid nanofluid, a new correlation was suggested using experimental data. The maximum value of deviation margin was 1.58%. Comparisons showed an excellent agreement between the correlation outputs and experimental data.

Nor Azwadi et al, [12] taken comprehensive literature on synthesis of hybrid nanoparticles, hybrid nanofluid and thermo physical properties of hybrid nanofluids. The process of preparation, factors affecting performance of hybrid nanofluid has been extensively discussed. Meanwhile, in this review thermal characteristics of hybrid nanofluid were found to be higher in comparison to the base fluid and fluid containing single nanoparticles respectively.

Hybrid nanofluids have shown interesting characteristics in terms of heat transfer performance but as a new type of working fluids there are some challenges in their development. Firstly, there is lack of agreement between results obtained by different researchers; secondly, there is lack of theoretical model that can predict the exact behavior of the fluids. Thirdly, in the preparation method, different methods lead to different result for a given nanofluid and volume fraction. Most of the nanoparticles used in the synthesis of hybrid nanofluid are hydrophobic in the process of making the hydrophilic their characteristics in some instances are affected. Stability is one of the important factor that affect the performance of hybrid nanofluid, lack of good stability adversely affect the nanofluid. It has been observed by previous researchers stability of some nanofluid deteriorates over a long period of time.

Sadegh et al. [13] carried out study on preparation, thermal conductivity and dielectric strength of Ag- WO_3 hybrid nanofluid while the base fluid was transformer oil. Applied nanofluids have been prepared by a one-step method known as Electrical Explosion of Wire (E.E.W). Measuring zeta potential of utilized hybrid nanofluids in three different weight fractions of 1%, 2% and 4% has been experimentally carried out. Thermal conductivity of applied nanofluids in temperature range of 40–100 °C has been measured by a KD2-Pro thermal analyzer. The results showed that thermal conductivity of applied hybrid nanofluids increased by 41% in higher weight fraction and 100 °C. Finally, it has been observed that electrical conductivity of hybrid nanofluids decreased to 35 kV in 4% wt. 1.

Mechiri et al. [14] investigated Vegetable oils (Ground nut) to serve as a possible substitute for non-biodegradable mineral oils, which are currently being used as metal cutting fluids in machining processes. In-situ synthesis of Copper (Cu) and Zinc (Zn) combined hybrid particles is performed by mechanical alloying with compositions of 50:50; 75:25; 25:75 by weight. Characterizations of the synthesized powder were carried out using XRD, Particle size analyzer, FE-SEM and TEM. Hybrid nanofluids with all the three combinations of hybrid nanoparticles were prepared by dispersing them into base fluid (vegetable oil). The thermo physical properties, such as thermal conductivity and viscosity were studied for various volume concentrations and at a range of temperatures. Experimental results have shown enhancement in thermal conductivity in all cases and also increase in viscosity. The enhancement in viscosity is similar in all three combinations as the particle size and shape are utmost identical. The enhancement in thermal conductivity is higher in Cu-Zn (50:50) results in better enhancement in thermal conductivity due to the Brownian motion of the particles and higher thermal conductivity of the nanoparticles incorporated.

Masoud Afrand et al. [15] experimentally investigated, the effects of temperature and nanoparticles concentration on the rheological behavior of Fe_3O_4-Ag/EG hybrid Nano fluid. Stable and homogeneous suspensions were prepared in solid volume fractions of 0.0375%, 0.075%, 0.15%, 0.3%, 0.6% and 1.2%. Viscosity measurements were performed at different shear rates (12.23–122.3 s-1) under temperatures ranging from 25 °C to 50 °C. Finally, the consistency index and power-law index were obtained from curve-fitting on shear stress-shear rate dependency. Curve-fitting results showed that all power-law indices were in the range of 0.5339–0.6706, indicating that the Nano fluid samples possessed shear-thinning behavior at all temperatures considered. Moreover, the results revealed that consistency index significantly increased with an increase in the solid volume fraction and decreased with enhancing temperature.

Hamida et al. [16] carried out to provide a wider knowledge and information on heat transfer performance of TiO_2 nanofluids. The forced convection heat transfer is conducted at Reynolds number of 3000–24,000 under constant heat flux boundary conditions. The TiO_2 nanofluid is prepared at 0.5–1.5% volume concentration and the thermal conductivity and dynamic viscosity were measured for 30–70 °C. The heat transfer performance was evaluated at three different bulk temperatures for its heat transfer coefficient and friction factor; 30, 50 and 70 °C. The thermal conductivity and viscosity enhanced with the increase in volume concentration. The friction factor of TiO_2 nanofluids is slightly increased with the increase of concentration at approximately 1.1 times of base fluid. The performance factor, h′ of the TiO_2 nanofluids is significantly influenced by the thermal properties, concentration, temperature, and Reynolds number.

Xianpeng et al, [17] investigated the lubrication performances of Al_2O_3/SiC Nano fluid minimum-quantity lubrication (MQL) grinding in accordance with recent technologies used in conducting minimum-quantity lubrication grinding with nanofluids. The mean grain size of the Al_2O_3 and SiC nanoparticles (NPs) was set to 50 nm, and the difficult grinding Ni-based alloy was used as the work piece material in the experiment. Grinding force was measure by using a three component dynamometer and then used to calculate grinding force ratio (R). Work piece surface roughness was measured by a roughness tester. Five groups of NPs were mixed with synthetic lipids at a mass fraction of 6%. The lipids were then used as the grinding fluid for the nanofluid MQL grinding. Results showed that, compared with pure SiC NPs, pure Al_2O_3 NPs obtained lower R = 0.3, lower specific grinding energy (U = 75.93 J/mm3), and lower surface roughness (Ra = 0.386 μm), indicating better lubrication performance. The mixed NP consisting of Al_2O_3 and SiC NPs achieved even lower R and surface roughness than pure NPs because of the "physical synergistic effect." The optimal ratio of the effect of mixed NPs was explored based on this finding.

Akilua et al. [18] were undertaken the influence of temperature on the electrical conductivity, pH, thermal conductivity and viscosity of SiC (29 nm) nanofluid in a binary mixture of glycerol and ethylene glycol. The experimental results reveal that the electrical conductivity and pH of the base liquid are unaffected by increased temperature. In contrast, the electrical conductivity of the SiC nanofluid increases while the pH decreases with increasing temperature. Moreover, thermal conductivity and viscosity show strong response to temperature increase. At 0.3 and 1.0 vol%, enhancement in thermal conductivity with temperature between 30 and 60 °C was observed to be 2.6% and 6.8%, respectively. Viscosity of the base liquid and SiC nanofluid decreased steadily with increasing temperature. A decrease of about 51% and 113% was found between 30 °C to 60 °C at 0.3 and 1.0 vol% compared to the base liquid.

Mohammad et al. [19] investigated the effects of temperature and volume fraction on thermal conductivity of SWCNT– Al_2O_3/EG hybrid nanofluid. Single-walled carbon nanotube with outer diameter of 1–2 nm and aluminum oxide nanoparticles with mean diameter of 20 nm with the ratio of 30 and 70%, respectively, were dispersed in the base fluid. The measurements were conducted on samples with volume fractions of 0.04, 0.08, 0.15, 0.3, 0.5, 0.8, 1.5 and 2.5. In order to investigate the effects of temperature on thermal conductivity of the nanofluid, this characteristic was measured in five different temperatures of 30 °C, 35 °C, 40 °C, 45 °C and 50 °C. The results indicate that enhancement of nanoparticles' thickness in low volume fractions and at any temperature cause a considerable increment in thermal conductivity of the nanofluid. In this study, the highest enhancement of thermal conductivity was 41.2% which was achieved at the temperature of 50 °C and volume fraction of 2.5%. Based on the experimental data, an experimental correlation and a neural network are presented and for thermal conductivity of the nanofluid in terms of volume fraction and temperature. Comparing outputs of the experimental correlation and the designed artificial neural network with experimental data, the maximum error values for the experimental correlation and the artificial neural network were, respectively, 2.6 and 1.94% which indicate the excellent accuracy of both methods in prediction of thermal conductivity.

Leonga et al. [20] suggested the purpose of review to explore the synthesis method used by the researchers to develop hybrid nanofluids. Apart from that, hybrid nanofluid's thermal conductivity, challenges and future direction of this field are discussed. Based on the review, it is found that carbon nanotube is often combined with other material to synthesize hybrid nanoparticles. Hybrid nanofluids exhibit improved thermal conductivity characteristic.

Muhammad Hafiz et al. [21] summarized the factors affecting the performance of hybrid nanofluid in enhancing the thermal performance of heat transfer systems. The mathematical correlations developed by researchers, which consists of thermal conductivity, viscosity, Nusselt number, friction factors and others models. It was observed that the performances of the hybrid nanofluids are normally determined by its volume concentrations, mixing ratios and stability of the dispersions. Thus, majority of the correlations established from the experiments are mostly as a functions volume concentrations of hybrid nanoparticles. Hybrid nanofluids have shown distinctive features in terms of heat transfer performance.

Nor Azwadi et al. [22] suggested a Hybrid nanofluid, a new class of nanofluids engineered by dispersing two different nanoparticles into conventional heat transfer fluid. Hybrid nanofluids are potential fluids that offer better heat transfer performance and thermo-physical properties than convectional heat transfer fluids (oil, water and ethylene glycol) and nanofluids with single nanoparticles. Scientific findings have indicated that hybrid nanofluid can replace single nanofluid since it provides more heat transfer enhancement especially in the areas of automobile, electro-mechanical, manufacturing process, HVAC and solar energy. In this paper, summarized the recent progress related to preparation methods of hybrid nanofluids, factors affecting their stability, methods of enhancing thermal properties and current applications of hybrid nanofluids.

Hybrid nanofluids have shown interesting characteristics in terms of heat transfer performance but as a new type of working fluids, there are some challenges in their development. Firstly, there is lack of agreement between results obtained by different researchers; secondly, there is lack of theoretical model that can predict the exact behaviour of the hybrid nanofluids. Thirdly, in the preparation method, different methods lead to different result for a given nanofluid and volume fraction.

Pritam Kumar Das, [23] carried out a comprehensive review, on the enhancement of effective thermal conductivity of nanofluids and to discuss the heat transfer mechanisms. This article also discusses several factors affecting thermal conductivity; including types of nanoparticles, solid volume fraction, different base fluids, temperature, particle size, pH, sonication, surfactants and various mechanisms of thermal conductivity enhancement in nanofluid development are discussed. Furthermore synthesis, preparation methods, thermal conductivity, and challenges of hybrid nanofluids are also discussed. Hybrid nanofluid exhibits improved thermal conductivity characteristic than normal nanofluids. However results indicate that the selection of proper hybrid nanoparticles is a major challenge for preparing stable nanofluids.

Baojie Weia et al. [24] investigated the thermal conductivity and rheological behavior of SiC/TiO_2-diathermic oil based nanofluids, which is rarely introduced by previous literatures. Diathermic oil has high boiling point, low vapour pressure and low pour point, so it has been widely used as a heat carrier in heat transfer systems. Due to the excellent thermo-physical property of nanofluids, a kind of hybrid nanoparticles (SiC/TiO_2) was dispersed in diathermic oil to fabricate nanofluids with concentration up to 1 vol%. And there was no visually observable sedimentation or stratification even after ten days. As two characteristics of thermo-physical property, the thermal conductivity and viscosity were measured under the same conditions respectively, and the experimental results showed that the thermal conductivity of nanofluids increased with increasing volume fractions of nanoparticles and increasing of temperature.

M. Hemmat [25] investigated experimentally the rheological behavior of MWCNT-MgO (10–90%) hybrid nanofluids in the base fluid, SAE40 engine oil. This study indicates that an increase in the volume fraction and decrease in temperature cause an increased in viscosity. Also it was shown that these nanofluids have a non-Newtonian behavior in terms of shear –thinning. It was inferred by investigating the power law index and consistency index. Both of these parameters have inverse relation with temperature and an increase in volume fraction cause an increase in consistency of volume fraction of more than 1%. Also an empirical relation is provided to estimate the viscosity with high accuracy Comparing the data with experimental results of MWCNT-SiO_2 (50–50%) / SAE40 oil and MWCNT/SAE40 oil nanofluids shows that a wide range of nano- lubricants for engineering applications are available which can be used in mechanical equipment especially in vehicles engines. These results can be used according to the needs of each industry and its requirements.

Georgiana Madalina et al. [26] explores two mono-component and one bi-component nanofluid and, to be more specific, it deals with the viscosity study of stabilized $Al2O_3$, SiO_2 water based nanofluids and their hybrid ($Al2O_3$ + SiO_2 nanoparticles diluted in water). Experimental research showed a non-Newtonian behavior of all tested nanofluids. Alumina nanofluids and the two studied hybrid nanofluids have shear-thinning behavior and silica nanofluid have a shear thickening behavior. More exactly, the overall relative viscosity is higher for alumina nanofluids if compared to SiO_2 nanofluid and, by replacing 0.5% of SiO_2 with alumina, the viscosity increases if compared to results for SiO_2 nanofluid. The viscosity variation with temperature was experimentally studied for the case of hybrid nanofluids, underlying the decreasing of viscosity while temperature rise and the low hysteresis behavior while proposing two equations for the viscosity variation as temperature was increasing.

Ranga Babu et al. [27] summarizes the contemporary investigations on synthesis, thermo-physical properties, heat transfer characteristics, hydrodynamic behavior and fluid flow characteristics reported by researchers on different hybrid nanofluids. This review also outlines the applications and challenges associated with hybrid nanofluid and make some suggestions for future scope of research in this area.

By using hybrid nanofluids, the thermal conductivity and heat transfer characteristics were further enhanced compared to mono nanofluids. For example, Nusselt number of Al_2O_3-Cu/DI water hybrid nanofluid is enhanced by 13.56% whereas for Al_2O_3/water nanofluid it is enhanced by 6.09% compared to the base fluid. This paper comprehensively summarizes the various synthesizing methods adapted by the researchers to produce different kinds of nanocomposites.

Friction factor and pressure drop are relatively more for the hybrid nanofluids compared to mono nanofluids and base fluid. Inclusion of hybrid nanoparticles develops more wall shear and this wall shear rate increases with volume fraction.

Alina Adriana et al. [28] summarizes the most of the recent research on the preparation, thermo physical properties, correlations and heat transfer characteristics of hybrid nanofluids and compares some fully and partially described hybrids. The heat transfer characteristics of different hybrid nanofluids were reviewed and numerically compared using a 3D tube model. The CFD analysis has led to the following conclusions, the heat transfer performance in a straight circular tube is amplified by implementing hybrid nanofluids or by suspension of hybrid nanoparticles in comparison with that of pure water.

Sahid et al. [29] presents an experimental investigation on properties and stability of hybrid nanofluids (TiO_2 and ZnO) in water-ethylene glycol mixture. The nanofluids are important in heat enhanced due to its inherent operative performance. The properties of TiO_2 and ZnO nanoparticle dispersed in mixture of water and ethylene glycol (EG) were considered in this study. The outcome of base fluid proportion (water: EG) to hybrid nanofluids was investigated. Hybrid nanofluids with different volume concentration up to 0.1–1.5% were prepared with 21 nm particle size of TiO_2 and 10–30 nm ZnO nanoparticle. The nanoparticle were suspended in various ratio of TiO_2 : ZnO including 70:30, 80:20 and 90:10 by volume percent. The measurements of viscosity were performed using Brookfield LVDV III Ultra Rheometer for hybrid nanofluid temperature of 50–70 °C, while the measurements of thermal conductivity were performed using KD2-Pro thermal analyzer.

M.F. Nabila et al. [30] experimental work were focused on the thermal conductivity and dynamic viscosity of TiO2-SiO2 nanofluids in a mixture of water and ethylene glycol (EG) with volume ratio of 60:40. The stable suspension of TiO_2-SiO_2 prepared at volume concentrations of 0.5–3.0%. The measurements of thermal conductivity and dynamic viscosity were performed at a temperature range of 30–80 °C by using KD2-Pro thermal analyzer and Brookfield LVDV III Ultra Rheometer, respectively. The thermal conductivity of TiO_2-SiO_2 nanofluids was improved by increasing the volume concentration and temperature with 22.8% maximum enhancement. Besides, the viscosity of TiO_2-SiO_2 nanofluids showed evidence of being influenced by nanofluid concentration and temperature. Additionally, the TiO_2-SiO_2 nanofluids behaved as a Newtonian fluid for volume concentration up to 3.0%. The properties enhancement ratio suggested that TiO_2-SiO_2 nanofluids will aid in heat transfer for concentrations of more than 1.5% and within the range of the temperature studied.

K.A. Hamid et al. [31] studied hybrid nanofluid properties such as thermal conductivity and due to its ability to improve heat transfer compared to conventional heat transfer fluids, nanofluids as a new coolant fluid are widely investigated. This paper presents the thermal conductivity of TiO_2-SiO_2 nanoparticles dispersed in ethylene glycol (EG)-water. The TiO_2-SiO_2 hybrid nanofluids is measured for its thermal conductivity using KD2-Pro thermal analyzer for concentration ranging from 0.5% to 3.0% and temperature of 30, 50 and 70 °C. The results show that the increasing in concentration and temperature lead to enhancement in thermal conductivity. The maximum enhancement is found to be 22.1% at concentration 3.0% and temperature 70 °C. A new equation is proposed based on the experiment data and found to be in good agreement where the average deviation (AD), standard deviation (SD) and maximum deviation (MD) are 1.67%, 1.66% and 5.13%, respectively.

Mohammad Hemmat et al. [32] experimentally studied the rheological behaviour of TiO_2-MWCNT (45–55%) / 10w40 hybrid nano-oil.

In this study, firstly rheological behavior of a nano-oil was determined empirically and then an equation was presented by which this behavior can be predicted. Also neural network modeling was utilized for the purpose of prediction. When the experimental data is compared with the theoretical models, it is clearly observable that none of the models was capable of an appropriate prediction of the nano-oil behavior; therefore, curve fitting technique was utilized for achieving a new governing equation. On the other hand, behavior of the hybrid nano-oil was verified with neural network modeling. The results signify that output data of ANN are in good accordance with viscosity data.

Mohammad et al. [33] study deals with the measurement of thermal conductivity of SWCNTs-MgO/EG hybrid nanofluids and the modeling of experimental data using artificial neural network (ANN). Hybrid nanofluids are produced and tested at volume fraction of 0.05–2% and temperature range from 30 to 50 °C. The nanofluid's obtained data has been compared with experimental outcomes of single particle nanofluids of MgO and SWCNT in base fluid of Ethylene Glycol. The analysis shows that the alterations gradient of thermal conductivity increases with the rise of volume fraction of up to 1%, and then, the sensitivity decreases.

Munish Gupta et al. [34] presents a compressive review of the various methods used for the preparation of hybrid Nanofluid and study of thermo physical properties by various researchers reported in the literature. Hybrid nanofluids possess improved thermo physical properties as compared with the single nanoparticles based nanofluids. This review also discusses several factors affecting the thermo physical properties; including types of nanoparticles, solid volume fraction, different base fluid, stability, temperature, particle size, shape, pH, sonication, and surfactants. There are many contradictory results found in the literature on the influence of effective parameters on thermo physical properties. It has been observed that the thermo physical properties are affected by the mentioned parameters.

Amir Kakavandi et al. [35] investigated experimentally, the preparation, stability and thermal conductivity of the MWCNTs-SiC/Water-EG hybrid nanofluid. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) methods were used to characterize the nanoparticles. Nanofluid stability was monitored by DLS test. The thermal conductivity of the hybrid nanofluid was measured using the KD2-Pro thermal analyzer and the KS-1 sensor at a temperature range of 25–50 °C and a solid volume fraction range of 0–0.75%. According to the results, the thermal conductivity of the nanofluid increased further at higher concentrations of the nanoparticles. The maximum thermal conductivity of the nanofluid increased up to 33% relative to the base fluid at a temperature of 50 °C and a concentration of 0.75%. A correlation with high accuracy was obtained by fitting the experimental data. The correlation was used to calculate the thermal conductivity of the nanofluid. Given the desirable thermal properties of this nanofluid, it can be used as an alternative fluid in practical systems with high heat transfer potential in the field of heat transfer.

Hossein et al. [36] gives a brief introduction of nanofluid and its applications have been discussed the classical equations suggested for predicting the viscosity of nanofluids and their accuracy have been reviewed. The role of effective parameters on the nanofluid viscosity has also been reported, indicating an increase in the viscosity of the common fluids by increasing the nano-additives volume fraction and reducing it with increasing temperature. For the effect of increasing nano-additives size, different results (decreasing or increasing) on fluid viscosity have been reported. In addition, nanofluids made with carbon nanotubes are described according to the high heat transfer coefficient. Finally, the introduction of hybrid nanofluid and their comparison with mono nanofluids has been explained by the conclusion that hybrid nanofluids can well cover nanofluid weaknesses and improve its strengths.

Dhinesh Kumar et al. [37] suggested the presence of high thermal conductivity of nanofluid, higher exposed surface area of nanoparticles, good network between them and stability of network is required. Hence, new theories are required to interpret clearly the mechanism for the thermal conductivity enhancement of nanofluids considering several factors which includes stability of the nanoparticles in the suspension fluids, viscosity of the base fluid and characteristics of the nanoparticles such as size, aspect ratio, specific area, etc. which are not considered in the existing models. From the present review, it can be understood that hybrid nanofluid is a promising heat transfer fluid and extensive and systematic experimental research works have to be carried out to understand the science behind the anomalous enhancement in thermal and rheological properties and to develop various property models for a wide range of performance affecting parameters for the viable and sustainable commercialization of hybrid nanofluids in various fields of engineering in future.

Gabriela Huminic et al. [38] presents a review of recent results concerning thermo-physical properties (thermal conductivity, viscosity, density and specific heat) and heat transfer and flow characteristics of hybrid nanofluids used in various heat exchangers.

This review revealed that hybrid nanofluids, with few exceptions, have thermal conductivities and viscosities higher than their base fluid and increase with increasing nanoparticles concentration. Thus, the stability and the development of new methods for the hybrid nanofluids production, using less expensive equipment represents key objectives in this field. Because the hybrid nanofluids involve at least two different types of nanoparticles, their compatibility is also important factor.

Hong Wei et al. [39] reviews the preparation method, stability investigation method, thermo physical properties and heat transfer performance of hybrid nanofluid in various heat transfer applications. Apart from that, this review outlines challenges regarding hybrid nanofluid and some suggestions to improve future researches in this area.

To enhance stability of nanofluids produced, surfactants are used in order to disperse nanoparticles. Different type of surfactants added into nanofluids may produce different results. However, surfactant may degrade thermo physical properties of nanofluids when excessive amount is added.

Wayan Nata et al. [40] study aims to determine the effect of nanoparticle composition on the highest thermal conductivity value with the lowest agglomeration value. This research was conducted by dispersing Al_2O_3-TiO_2 nanoparticles in water with volume fraction of 0.1%, 0.3%, 0.5%, and 0.7% in the composition of Al_2O_3-TiO_2 ratio of 75%:25%, 50%:50%, 25%:75%. The synthesis was performed with a magnetic stirrer for 30 min. The tests were carried out in three types: thermal conductivity testing with KD2-Pro thermal analyzer, visual agglomeration observation and absorbance measurements using UV–Vis, wettability testing with HSVC tools and Image applications. The test results showed that the ratio composition ratio of 75% Al_2O_3-25% TiO_2 with a volume fraction of 0.7% resulted in an increase in optimum thermal conductivity which is 32.50%. With the best wettability and the longest agglomeration level.

Yan Liu et al. [41] investigated the viscosity of hybrid nanofluids containing two kinds of nanoparticles, a series of experiments are conducted on TiO_2–Ag/ engine oil, Al_2O_3–Ag/engine oil (a mixture of the volume ratio of 50:50) nanofluids under different shear rates and volume fractions. The results show that the viscosity decreases with increasing shear rate, which suggests TiO_2–Ag/ engine oil and Al_2O_3–Ag/engine oil hybrid nanofluids are both shear thinning fluids, whilst the viscosity of all samples enhances with the increase of volume fraction. Moreover, an interesting result is observed that the hybrid nanofluids have a lower viscosity than single particle nanofluids. **Muhammad and Hafiz** [42] conducted a studies on nanofluids containing single type nanoparticles and attributes of such colloidal mixture have been well elucidated and prospected. The cardinal objective of this study is to provide a comprehensive review on thermal conductivity of hybrid nanofluids by overviewing experimental, numerical and ANN (artificial neural networking) studies. Assorted factors that affect thermal conductivity such as nanoparticle type, concentration of nanoparticles, types of base fluid, size of nanoparticle, temperature, addition of surfactant, pH variation and sonication time are analyzed in present paper.

Increase in temperature and concentration had upper limits to enhance thermal conductivity beyond which a decline in thermal conductivity was observed.

Nearly all correlations developed from experiments to predict thermal conductivity of hybrid nanofluids, were function of temperature and volume fraction of nanoparticles. The established correlations were applicable for narrow range of depending parameters (temperature and concentration). Augmentation in Brownian motion, micro convection, clustering of nanoparticles, percolation effect, electrostatic repulsive forces and diffusive heat conduction were primary reasons for increase in thermal conductivity of hybrid nanofluids.

Amin Asadia et al. [43] investigated the heat transfer capability of Mg $(OH)_2$/ MWCNT- engine oil hybrid nano-lubricant. First, the effects of temperature and Solid volume fraction on the dynamic viscosity and thermal conductivity of Mg $(OH)_2$/MWCNT- engine oil hybrid Nano lubricant have been experimentally investigated. The experiments have been conducted in various temperatures (25 °C, 30 °C, 35 °C, 40 °C, 45 °C, 50 °C, 55 °C, and 60 °C) and solid concentrations (0.25%, 0.5%, 0.75%, 1%, 1.5%, and 2%). Based on the measurements, it is found that the studied nano-lubricant showed Newtonian behavior in all the studied temperatures and solid concentrations. Furthermore, the experimental results indicated that the dynamic viscosity of the nano-lubricant increases with an increase in solid concentration while it decreases with an increase in temperature. The thermal conductivity of the nanofluid showed increasing trend as the solid concentration and temperature increased. The minimum and maximum enhancement were about 13% and 50%, respectively. Based on experimental data, two new trustworthy correlations to predict the dynamic viscosity and thermal conductivity of the nano-lubricant has been proposed.

Hafiz Muhammad et al. [44] conducted a work on hybrid-nanofluids to explore their heat transfer and physical features. Some of the known ways of stabilizing these fluids include sonication, addition of dispersant, and controlling their pH value. Comprehensive details of aforementioned techniques along with associated challenges as well as stability determining methods such as Zeta-potential, sedimentation period, spectral absorption, and centrifugation, have been presented in this review. Controlling the nanoparticle size, concentration, and rheological aspects leads to better stability. Considering the thermal features and stability period, potential of different hybrid-nanofluids for future work has been discussed in the concluding section of this paper.

Thermal features like heat transfer coefficients have been reported to decrease as the time passes. This scenario indicates disappearing stability. Several methods have been devised by the researchers to obtain optimum stability such as pH control method, surfactant addition method, chemical treatment, magnetic stirring, ultra sonication, etc. Most widely used surfactant is CTAB. Appropriate chemical treatment is one of the best tools to obtain longer stability.

Santana et al. [45] studied the enhancement of thermos-physical and lubricating properties of the vegetable oil with silicon carbide nanoparticles inclusion. Three level of Nano lubricant concentrations were prepared with dispersion of 0.35, 0.70 and 1.05 wt% silicon carbide nanoparticles and their properties evaluated. Thermal conductivity of Nano lubricants was observed to decrease with increase temperature but increases with increased concentration level. Viscosity of vegetable oil based Nano lubricants increases with increase of volume concentration and decrease with increase of temperature. The highest thermal conductivity enhancement ratio was observed to be 1.038. Increase of concentration increase the viscous nature of the fluid under temperature variation thereby strengthening the ability of vegetable oil based Nano lubricant to form lubricating film between contacting surfaces that aid friction reduction and faster dissipation of heat when compared with pure vegetable oil that disintegrate under higher temperature.

Hafiz Muhammad et al. [46] focused on the various techniques used for the preparation of TiO_2 nanofluids. On the different synthesis techniques and important physical properties (thermal conductivity and viscosity) that need to be considered very carefully during the preparation of TiO_2 nanofluids for desired applications. The primary step involved in the preparation of nanofluid is the production of nano-sized solid particles by using a suitable technique, and then these particles are dispersed into base fluids like oil, water, paraffin oil or ethylene glycol. However, nanofluid can also be prepared directly by using a liquid chemical method or vapor deposition technique (VDT). Nanofluids are mostly used in heat transfer applications and the size and cost of the heat transfer device depend upon the working fluid properties, thus, in the past decade scientists have made great efforts to formulate stable and cost-effective nanofluids with enhanced thermo physical properties.

Vishnu Narayanan et al. [47] focuses on the recent advancements in the study of nanofluids such as preparation methods, stability of nanofluids and presents the extensive area of applications. Studies and experiments have to be done to improve the stability of metallic based nanofluids and also to attain more stable solution for metal oxide based nanofluids. Research must be carried for the development of nanofluids with low viscosity.

AliH et al. [48] in their study used water as a base fluid and nano-silicon carbide as an additive to improve the thermal conductivity of the resulted nanofluid and its thermo physical properties were studied using five surfactants. The stability time of nanofluid was the main variable investigated. The deposition process significantly reduces the thermal conductivity of nanofluids and thus reduces heat transfer. The used surfactants are: ammonium cetyl-cetyl (CTAB), sodium dodecyl sulfate (SDS), tannic acid + ammonia solution, dodecyl benzene sulfonate (SDBS), and Sodium deoxycholate. Ammonium cetyl (CTAB) and tannic acid + ammonia solution gave the highest stability period (more than two months) with ultra-sonication mixing time for six hours by adding 0.1 ml. The addition of larger amounts of surfactant (more than 0.75 ml) increased the stability time for all nanofluids used. The maximum stability time achieved was 88 days when cetyl (ammonium cTAB) was added by 0.5 ml. The density, viscosity, and thermal conductivity measurements showed that there was no significant change with the change of the surfactant used. The maximum stability time was 93 days when ammonium cetyl (CTAB) was addedby1.0 ml.

Amin Asadia et al. [49] investigated Al_2O_3-MWCNT/thermal oil hybrid nanofluid as a new class of cooling fluid for heat transfer and energy management applications in automotive industry and a heating fluid for the hot-side of thermoelectric modules. The stability of the prepared nano-oil has been investigated by the means of Zeta potential analysis. The thermo physical and rheological properties of the nano-oil have been experimentally investigated over the different range of temperatures (from 25 °C to 50 °C) and solid concentrations (from 0.125% to 1.5%). The nanofluid showed Newtonian behavior over the studied range of temperatures and solid concentrations. It has also been observed that the dynamic viscosity increased as the solid concentration increased.

Ahmet Selim et al. [50] experimental study includes measurement of thermal conductivity of distilled water-based CNT-SiO_2 hybrid nanofluids. In the current work, the thermal conductivity of hybrid nanofluids was highlighted due to its direct influence on heat transfer relating with Nusselt number, conductance etc. Firstly, thermal conductivity values have been measured with a device, then the validation of the pure fluid's experimental results were performed by the values in fundamental sources. The main purpose was to increase thermal conductivity which had been carried out.

Vikash Kumar and Rashmi Sahoo [51] investigated thermal conductivity and viscosity analysis of Al_2O_3/ CuO (50/50) hybrid nanofluid in various mass fractions of ethylene glycol (EG) and propylene glycol (PG) binary base fluid. Hybrid nanofluid with vol. fraction range limited to 1.5% and within the higher temperature range of 50 °C to 70 °C is considered for thermal conductivity and viscosity analysis. Impact on viscosity and conductivity models with various shape nanoparticles, i.e., spherical, cylindrical, brick, platelets, and blades have been discussed and were compared in EG and PG binary base fluids. Also, the analysis extends to the prediction for the stability with zeta potential and synthesis of spherical shape Al_2O_3/CuO hybrid nanofluid with X-ray diffraction (XRD) and scanning electron microscope (SEM). The theoretical analysis revealed that thermal conductivity of Al_2O_3/CuO hybrid nanofluid in EG binary base fluid is lower compared to in PG binary base fluid. The thermal conductivity is observed to be higher in spherical and cylindrical shape nanoparticle compared to bricks, blades, and platelets shape nanoparticles. Optimum viscosity of Al_2O_3/CuO hybrid nanofluid is observed at 50% EG and 30% PG of the binary base fluid. Hybrid nanofluid in 30% of PG as binary base fluid results 16.2% higher dynamic viscosity compared to pure PG base fluid for a volume concentration of 2%. Zeta potential measurement results in the stability of spherical Al_2O_3-CuO/ (50/50) EG/W hybrid nanofluid, and it may be considered as a heat transfer fluid.

Ansari et al. [52] experimentally investigated the preparation method, stability, measurement, and modeling of the thermal conductivity of water/graphene oxide-silicon carbide nanofluid. In this study, the nanofluid was prepared via a two-stage method. Moreover, the SEM and XRD tests were used to investigate surface and atomic structure of nanoparticles. A probe-type ultrasonic stirrer was used to achieve stability and homogenized distribution of particles in the base fluid. Then, the nanofluid stability was assessed using the DLS test. According to the results, the base fluid contained nano-sized particles. Moreover, the thermal conductivity measurement of the hybrid nanofluid was carried out in the temperature and volume concentration ranges of 25–50 °C and 0.05–1 vol%, respectively. The experimental variables were the Nano fluid's temperature and volume concentration. Results showed that the thermal conductivity of the nanofluid increased with increasing volume concentration and temperature. Although nanoparticle concentration has a greater impact than temperature, changes in thermal conductivity are greater at higher temperatures. The greatest increase in thermal conductivity of nanofluid was 33.2% at the concentration of 1 vol% and temperature of 50 ◦C. To calculate thermal conductivity of this nanofluid, a highly accurate experimental equation was developed using the laboratory data curve fitting method.

Hamza babar et al. [53] study summarizes the work of different investigators and discusses the critical factors affecting the viscosity of hybrid nanofluids such as temperature, particle concentration, pH value, particle size and morphology with a concise discussion on the reasons reported in the literature for the viscosity augmentation. Furthermore, the models developed by different investigators have also been discoursed with specified limitations. Comparison between the viscosity of mono and hybrid nanofluid is also presented comprehensively. It is observed that most of the studies considered the effect of particle concentration and temperature that the effect of these factors is more significant. Water-based nanofluids delivered better results in comparison of ethylene glycol-based nanofluids while the oil-based nanofluids preferred in the applications where the pumping power is not more significant. It has been noticed that the fluids containing tube shaped nanoparticles comparatively showed enhanced viscosity than that of spherically shaped nanoparticles.

Suleiman Akilu et al. [54] experiment carried out on data of viscosity and thermal conductivity (TC) of ethylene glycol (EG)-based hybrid nanofluids (HyNFs) dispersed with a SiC–CuO/C Nano composite (NC). The rheological behaviour and dynamic viscosity have been analyzed with a computer controlled rotational rheometer over a temperature range from 298.15 to 353.15 K and shear rate from 20 to 200 s^{-1}. The TC was measured using transient hot-wire method for NF concentrations up to 3.13 wt%. The effect of the temperature and volume fraction of the nanoparticles (NPs) on the thermo physical properties was examined under atmospheric pressure. The experimental findings revealed that the TC increases with the concentration and temperature, while the viscosity increases with concentration and decreases with temperature as expected. The enhanced properties of the HyNF could be attributed to the synergetic effects of the composite particles and the underlying physical mechanism in the fluid medium. The existing theoretical models failed to predict the experimental data. Herein, a new correlation is presented as a function of concentration and temperature for the TC and viscosity.

Ramadan et al. [55] investigate the stability of tri-hybrid nanofluids suspended in Water-Ethylene Glycol (EG) mixture. The tri-hybrid nanofluids were prepared at a volume concentration of 0.05–0.3% using the two-step method. Three types of nanoparticles used namely Al2O3, TiO2 and SiO2, and dispersed in a base fluid of water/EG. The investigation on the stability of the hybrid nanofluids in the present study is conducted through UV–Vis, zeta potential, sedimentation and micrograph observation. The findings from the investigations on the visual stability of sedimentation show that the differences in concentration (0.05, 0.1, 0.2, and 0.3%) have been low in day 14. It was found that 10 h sonication time is the most suitable period for sonication to obtain a stable suspension.

Amin Asadi et al. [56] has taken the review aims to present the recent advances in the preparation methods and thermo physical properties measurements of oil-based nanofluids. Effects of various parameters such as nanoparticle concentration, size, and temperature on the values of properties including thermal conductivity, viscosity, density, and specific heat are reviewed. The correlations available for the properties of oil-based nanofluids are gathered from the literature that could be a worthy source for those who aim to work on oil-based nanofluids.

Anderson Gallego et al. [57] work aimed at accurately measuring some thermo physical properties of Al_2O_3 nanofluids stabilized with SBDS. Initially, a design of experiments with multiple nanofluids was analysed and, afterward, the nanofluids with greater temporal stability were selected. The thermo physical properties (such as thermal conductivity, viscosity, and surface tension) of those nanofluids were measured. The following are the results of this study use of SDBS was observed to play a key role in the thermo physical properties under study because thermal conductivity, viscosity, and surface tension depend directly on surfactant content. For that reason, the nanofluid with Al_2O_3 and SDBS concentrations of 0.5 wt% and 0.32 wt%, respectively, exhibited the highest temporal stability in this work; however, the use of a surfactant had a direct negative effect on surface tension and thermal conductivity and a positive effect on viscosity. The nanofluids with Al_2O_3 and no surfactant showed pseudo plastic behaviour and their nanoparticle concentration increased.

Sylwia Wcis, [58] is discussed different ways of stabilizing nanofluids, which seems to be one of the most challenging tasks in nanofluid treatment. Other future challenges concerning mono and hybrid nanofluids are also thoroughly discussed. Moreover, a quality assessment of nanofluid preparation is also presented. Thermal conductivity models are specified as well and new representative mono and hybrid nanofluids are proposed.

Yanping Du & Xiao Yuan [59] extensively reviewed the improved stability of coupled hybrid nano suspensions feasibility in the applications of heat and mass transfer and phase behavior related fields. It is revealed that the thermal conductivity and phase behaviour of hybrid nanoparticles are the dominant factors that need to be examined to improve the abilities in heat transfer and colloidal control.

Mixed approach and coupled approach for achieving superior dispersion stability of hybrid nano suspensions were specifically introduced. By using the coupled approach, the performance of phase behaviors can be largely promoted, preventing the nanoparticle aggregation as a result of the chemical bond formed in the fabrication process.

N.R. Dhar et al. [60] compares the mechanical performance of MQL to completely dry lubrication for the turning of AISI-1040 steel based on experimental measurement of cutting temperature, chip reduction coefficient, cutting forces, tool wears, surface finish, and dimensional deviation. Results indicated that the use of near dry lubrication leads to lower cutting temperature and cutting force, favorable chip–tool interaction, reduced tool wears, surface roughness, and dimensional deviation.

MQL with the present technique has reduced flank wear and hence is expected to improve tool life. Surface finish and dimensional accuracy improved mainly due to reduction of wear and damage at the tool tip by the application of MQL. Such reduction in tool wear would be either improvement in tool life or enhancement of productivity allowing higher cutting velocity and feed.

Anuj Kumar Sharmaa et al. [61] prepared a new nanofluid by mixing Al_2O_3 nanoparticles in conventional cutting fluid at different concentrations. The prepared nanofluid is characterized for its thermal conductivity and viscosity at all nanoparticle concentrations. Furthermore, its machining performance is examined in turning work piece of AISI 1040 steel using minimum quantity lubrication (MQL) technique. The results are also compared with that of dry machining and wet/MQL machining using conventional cutting fluid. The experimental study clearly reveals that performance of Al_2O_3nanofluid in terms of surface roughness, tool wear, cutting force and chip morphology is found to be better compared to dry machining, wet machining with conventional cutting fluid and MQL using conventional cutting fluid.

Vamsi Krishna Pasam et al. [62] are popularly used Cutting fluids to reduce the friction and associated effects in machining. However, due to the hazardous effects of these fluids on the workers' health and ecology, their usage is often discouraged. This has given rise to the concept of Minimum Quantity Lubrication (MQL). The present work focuses on preparation and testing of vegetable oil–based micro and nano cutting fluids in MQL. Two different solid lubricants- boric acid (H_3BO_3) and molybdenum disulphide (MoS_2) were dispersed in the coconut oil as micro/nano particles. The formulated fluids were used in machining to study the performance. It was observed that nanofluids out performed microfluids at high cutting speeds, but at lower speeds, the performance was identical. Optimization and economic analysis was carried out to study the viability of the fluids. It was found that, though performance of the nanofluids is better, microfluids are more economical.

Domnita Fratila and Cristian Caizar [63], studied the influence of process parameters and cooling lubrication method in turning of AISI 1045 under finishing conditions. Tests have been performed in dry conditions (dry cutting, DC), using the minimal quantity lubrication technique (MQL), and also in flood cooling (FC) conditions, using a carbide insert tool.

Response surface methodology and analysis of variance were used for the experimental design. Cutting depth, feed rate, spindle speed, cutting fluid type, and flow rate were considered as independent variables. Analysis of variance (ANOVA) was used to determine the effect of machining parameters on surface roughness, their individual contribution, and the effect of their interaction. Mathematical linear regression was proved to be the most appropriate method in order to approximate the relationship between surface quality and finish turning process parameters. Numerical and graphical optimizations show the minimal level of depth of cut, the maximum cutting speed, and the maximum lubricant flow rate resulted in a better quality of machined surface.

3. Research findings

Many researchers have used various nano composites to make hybrid nano-fluids, here it is summarized;

References	Nano Particle / Base Fluid	Research Findings Application / Result
[1]	Al_2O_3 Deionized water	The thermal conductivity of nanofluids increases remarkably with increasing given0.1%, 0.33%, 0.75%, 1%, 2%) volume fraction of nanoparticles. nanofluids behave as Newtonian fluids
[4]	MWCNT/g- Al_2O_3	The thermal conductivity reached up to 20.68% at a 0.1% volume fraction of hybrid, for a gum arabic (GA) based nanofluid.
[5]	TiO_2 Sodium Dodecyl Sulfate (SDS)	The results revealed that 3-h ultrasonic bath process with the addition of 0.1 wt% of surfactant can be the most stable suspension with the highest thermal conductivity for further applications within 1 month
[6]	Ag/TiO_2 water	Concentrations are measured at temperatures ranging from 15 to 40 °C. As a result, the present study confirms that the thermal conductivity of TiO_2 based solution can be improved by introducing the flattened "Ag" particles.
[7]	Cu–TiO_2	The test results reveal that the convective heat transfer coefficient, Nusselt number and overall heat transfer coefficient were increased by 52%, 49% and 68% respectively, up to 1.0% volume concentration of Hy NC.
[10]	TiO_2/ZrP	The surface of nanoplatelets is the main reason for improving stability, and the viscosity of exfoliated TiO_2/ZrP couples suspensions are much higher than TiO_2 suspensions.
[11]	f-MWCNTs– Fe_3O_4/EG	The maximum value of deviation margin was 1.58%. Comparisons showed an excellent agreement between the correlation outputs and experimental data.
[13]	Ag- WO_3/ transformer oil	The results showed that thermal conductivity of applied hybrid nanofluids increased by 41% in higher weight fraction and 100C. Finally, it has been observed that electrical conductivity of hybrid nanofluids decreased to 35 kV in 4% wt. 1.
[14]	Cu-Zn/ Vegetable oils (Ground nut)	The results have shown enhancement in thermal conductivity in all cases and also increase in viscosity for the given compositions of 50:50; 75:25; 25:75. But The enhancement in thermal conductivity is higher in Cu-Zn (50:50) results in better enhancement in thermal conductivity due to the Brownian motion of the particles and higher thermal conductivity of the nanoparticles incorporated.

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References	Nano Particle / Base Fluid	Research Findings Application / Result
[15]	Fe_3O_4-Ag EG	The given volume fractions 0.0375%, 0.075%, 0.15%, 0.3%, 0.6% and 1.2%. , the results revealed that consistency index significantly increased with an increase in the solid volume fraction and decreased with enhancing temperature.
[16]	TiO_2 water–EG	The friction factor of TiO_2 nanofluids is slightly increased with the increase of concentration at approximately 1.1 times of base fluid
[17]	Al_2O_3/SiC synthetic lipids	The mixed NP consisting of Al_2O_3 and SiC NPs achieved even lower R and surface roughness than pure NPs because of the "physical synergistic effect." The optimal ratio of the effect of mixed NPs was explored based on this finding.
[18]	SiC G	The Viscosity of the base liquid and SiC nanofluid decreased steadily with increasing temperature. A decrease of about 51% and 113% was found between 30 °C to 60 °C at 0.3 and 1.0 vol% compared to the base liquid.
[19]	SWCNT– Al_2O_3 EG	With the given volume fractions of 0.04, 0.08, 0.15, 0.3, 0.5, 0.8, 1.5 and 2.5. In order to investigate the effects of temperature on thermal conductivity of the nanofluid, this characteristic was measured in five different temperatures of 30, 35, 40, 45 and 50 °C. The highest enhancement of thermal conductivity was 41.2% which was achieved at the temperature of 50 °C and volume fraction of 2.5%.
[24]	SiC/TiO_2 Diathermic oil	The experimental results showed that the thermal conductivity of nanofluids increased with increasing volume fractions of nanoparticles and increasing of temperature. With the loading further increasing, the thermal conductivity of SiC/TiO_2 nanofluids is higher than SiC or TiO_2 nanofluids', and the maximum of thermal conductivity enhancement ratio is 8.39% at 1 vol%, the given temperature, which means that the samples are Newtonian fluid. And the higher the nanofluids concentration was, the larger value of their shear viscosity.
[25]	MWCNT-MgO SAE40 engine oil	The results of MWCNT-SiO_2 (50–50%) / SAE40 oil and MWCNT/SAE40 oil nanofluids shows that a wide range of nano- lubricants for engineering applications are available which can be used in mechanical equipment especially in vehicles engines.
[26]	Al_2O_3 - SiO_2 water	The result showed a non-Newtonian behaviour of all tested nanofluids.
[27]	Al_2O_3-Cu DI water	The relative viscosity of the hybrid nanofluid increased due to the formation of nano clusters in base fluid.
[29]	TiO_2-ZnO water-EG	It is more noticeable for higher concentration in TiO_2.
[30,31]	TiO_2-SiO_2 (EG)-water	The results demonstrated that the TiO_2-SiO_2 nanofluids behaved as a Newtonian fluid with volume concentrations of up to 3.0% [30], The results show that the increasing in concentration and temperature lead to enhancement in thermal conductivity at range of concentration studied [31]
[32]	TiO2-MWCNT 10w40	The viscosity, shear stress and shear rate variations it was cleared that either of the base oil and nano-oil were non-Newtonian fluids.
[33]	SWCNTs-MgO EG	The alterations gradient of thermal conductivity increases with the rise of volume fraction of up to 1%, and then, the sensitivity decreases.
[35]	MWCNTs-SiC Water-EG	The maximum thermal conductivity of the nanofluid increased up to 33% relative to the base fluid at a temperature of 50 °C and a concentration of 0.75%.
[40]	Al_2O_3-TiO_2 Water	The higher TiO_2 nanoparticle density causes faster agglomeration in TiO_2 nanofluid and hybrid nanofluid containing 75% TiO_2 nanoparticles.
[41]	TiO_2–Ag engine oil	The different materials with unlike morphologies mixture are more likely to reduce the viscosity than dissimilar nanoparticles mixture of just one material.
[43]	Mg $(OH)_2$/ MWCNT engine oil	Nanofluid would be advantageous in cooling applications compared to the base fluid, pure oil.
[49]	Al_2O_3-MWCNT Thermal oil	Dynamic viscosity increased as the solid concentration increased with the application of automotive industry and a heating fluid for the hot-side of thermoelectric modules.
[51]	Al_2O_3- CuO EG	Hybrid nanofluid in 30% of PG as binary base fluid results 16.2% higher dynamic viscosity compared to pure PG base fluid for a volume concentration of 2%.
[54]	SiC–CuO/C EG	The thermal conductivity increases with the concentration and temperature, while the viscosity increases with concentration and decreases with temperature as expected.
[61]	Al_2O_3 Vegetable Oil	The performance of Al_2O_3 nanofluid in terms of surface roughness, tool wear, cutting force and chip morphology is found to be better compared to dry machining, wet machining with conventional cutting fluid and MQL using conventional cutting fluid.
[62]	H_3BO_3/ MoS_2 coconut oil	It was found that, though performance of the nanofluids is better, microfluids are more economical. In the machining application.

Note: State of the Art papers are not mentioned in the above table and here mentioned the papers, [2,3,8,9,12,20,21, 22,23,28,34,36,37,38,39,42,44,45,46,47,48,50,52,53,55,56,57,58,59,60, and 62].

4. Research gap

Many researchers have used TiO2 & SiC as nano additives for increasing the performance of machining operation, but the hybrid nano fluid using proper combination of new class of hybrid nano fluid i.e. SiC and TiO2 need to be study. Necessity and benefits of implementing the performance of machining operation to prepare a new class hybrid nano fluid.

The physical and thermal properties of hybrid nano fluid have significant effects on lubricating properties. The literature survey shows that very little attention is given on characterization of such hybrid nano fluids.

Minimum Quantity Lubrication is sustainable lubrication mechanism for implementing the usage of hybrid bio-lubricant, effective Minimum Quantity Lubrication system need to be developed.

AISI 1040 steel widely used for various industrial applications. Hence it is require to develop an Eco Friendly cutting fluids in minimum quantity lubrication assisted machining for sustainable hybrid bio-lubricant system will add new dimensions.

5. Conclusion

Most of the work reported on hybrid nanofluids is having primary focus on the viscosity and thermal conductivity, whereas other properties such as density and specific heat are also important but ignored. A huge gap remains for detailed experimental studies for metallic and metal carbide based hybrid nanofluids to understand the thermo physical properties and development of theoretical models to be used in various engineering applications.

Priority should be given to research topics aiming at the selection of various hybrid materials, long-term stability of hybrid nanofluids, thermo physical properties, and heat transfer enhancement. However, cost of nanofluids may be major challenges behind the practical applications and substantial researches are still needed to identify and overcome many challenges for different applications.

Declaration of Competing Interest

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

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