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Thermo-physical properties of hybrid nanofluids and hybrid nanolubricants: A comprehensive review on performance

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ABSTRACT

Hybrid nanofluids and hybrid nanolubricants are very new types of research which can be prepared by suspending two or more than two dissimilar nanoparticles either in a mixture or composite form in the base fluids. The term hybrid can be considered as different materials which are a combination of physical and chemical properties to form a homogeneous phase. The main objective of synthesizing hybrid nanofluids/nanolubricants is to improve the properties of single materials where it has great enhancement in thermal properties or rheological properties that are better than individually conventional nanofluids/nanolubricants. This review summarizes the previous research on the thermo-physical properties of hybrid nanofluids/nanolubricants including methods of preparation, instrumentations, development and current progress, and hybrid performance in terms of heat transfer and pressure drop. Challenges and several applications using hybrid nanofluids/nanolubricants were also discussed. Recent studies showed that the hybrid nanofluids/nanolubricants improved the performance of the single type suspended nanoparticles. Various studies of hybrid nanofluids have been carried out to investigate the heat transfer performance and thermal conductivity; however, other thermo-physical properties such as viscosity, density and specific heat have been neglected. In addition, few studies on hybrid nanolubricants were done only for thermo-physical properties. Thus, a comprehensive study on heat transfer and the other thermo-physical properties are necessary to show the potential of hybrid in engineering applications.

and manufacturing. This is because of several factors such as (i) since the nanoparticle size is small, the pressure drop is minimal, (ii) the heat transfer rate that increases because of the higher thermal conductivity and large surface area of nanoparticles in a base fluid, and (iii) nanofluids are most suitable for rapid heating and cooling systems. Application of the nanofluids in the industries is prevented by several factors such as long term stability, increased pumping power and pressure drop, nanofluid thermal performance in turbulent and fully developed regions, lower specific heat of nanofluids and higher production cost of nanofluids [8]. For instance, the common applications of nanofluids and nanolubricants are engine cooling, engine transmission oil, lubricant in automotive air-conditioning compressor, nuclear system cooling, solar water heating, refrigeration, thermal storage, bio-medical applications, defence and space applications [1,14–22].

In a continuation of nanofluid research, a few papers have recently discussed the topic of hybrid nanofluids [23–26]. Hybrid nanofluids are considered as an extension of nanofluids in research work, which can be prepared by suspending two or more dissimilar nanoparticles either in mixture or composite form in the base fluids [23]. A hybrid material is a substance that combines the physical and chemical properties. Hybrid material consisting of carbon nanotubes (CNTs) have been used in electrochemical-sensors, bio-sensors and nanocatalysts, but the use of these hybrid nanomaterials in nanofluids has not developed as such [27]. The main objective of synthesizing hybrid nanofluids is to improve the properties of single materials where great enhancement in thermal properties or rheological properties can be achieved. Furthermore, the hybrid nanofluids are expected to achieve better thermal conductivity compared to a single type of nanofluid. Investigations on hybrid nanofluids, either experimental or numerical, are very limited. Until recently, only two review papers on hybrid nanofluids have been done by Sarkar et al. [23] and Sidik et al. [28]. However, both papers concentrated on the development and the recent progress and the review was only limited to the hybrid nanofluids.

Therefore, the objective of the present work is to provide a comprehensive review on the thermo-physical properties of hybrid nanofluids and hybrid nanolubricants. The paper also reviewed the methods of preparations, instrumentations, development and current progress of hybrid nanofluids/nanolubricants. Besides that, the performance of the hybrid nanofluids are also discussed for heat transfer, pressure drop and friction factor. Lastly, the challenges and several applications of hybrid nanofluids/nanolubricants were also discussed.

2. Development of hybrid nanofluids and hybrid nanolubricants

2.1. Methods of preparation

Table 1 summarized the methods of preparing the hybrid nanofluids/nanolubricants. The two-step method is the more dominant method compared to the one-step method. There are three types of base fluids used in preparing the hybrid solution, which are water and ethylene glycol for hybrid nanofluids whereas oil based fluids and lubricant for hybrid nanolubricants. A study by Jana et al. [29] used CNT-AuNP hybrid nanofluids. First, they used different volume fractions of CNT added into the water to produce different volume fractions of CNT suspensions whereas AuNP was added to DI water to produce AuNP suspensions. After that, AuNP suspensions were added to different volume fractions of CNT suspensions to achieve CNT-AuNP suspensions. Laurate salt and DI water were added in CuNP to form CuNP suspensions. Laurate salt acted as a catalyst to enhance the stability of CuNP suspensions. Then, CNT suspensions were added in CuNP suspensions to reduce the sedimentation of CuNP and improve the stability.

Ho et al. [30,31] prepared the PCM suspensions using interfacial polycondensation and emulsion technique. The PCM suspensions were formulated by mixing appropriate quantities of MEPCM particles with ultra-pure Milli-Q water in a flask. They then dispersed the nanoparticles in the solution using an ultrasonic vibration bath. The water based hybrid nanofluids was set up by scattering Al_2O_3 nanoparticles at different mass fractions in ultra-pure Milli-Q water by utilizing an attractive stirrer. Baby and Ramaprabhu [12] synthesized MWNT by catalytic chemical vapour deposition (CCVD) and hydrogen exfoliated graphene from graphite oxide (GO). The as-synthesized HEG was not solvent in water due to the exfoliation of oxygen containing functional groups from the specimen; making it hydrophobic. So as to make it hydrophilic, HEG and MWNT was functionalized in H_2SO_4 and HNO_3 acid medium. The nanostructure of the mixture was set up by mixing the same amounts of *f*-MWNT and *f*-HEG in a specified volume of water after functionalization. Further, the arrangement was ultrasonicated for 1 h and stirred for another 24 h. The final mixture was separated, dried

Table 1
Summary of preparation methods for hybrid nanofluids.

Authors	Base fluids	Materials	Methods
Baby and Ramaprabhu [12]	Water, EG	MWNT-HEG	Two-step method
Hemmat Esfe et al. [24]	Water, EG	Cu-TiO_2	Two-step method
Suresh et al. [25]	Water	Al_2O_3-Cu	Two-step method
Gou et al. [27]	Water	MWNT-silica	Two-step method
Jana et al. [29]	Water	CNT-CuNP/CNT-AuNP	Two-step method
Ho et al. [30]	Water	Al_2O_3-MEPCM	Two-step method
Ho et al. [31]	Water	Al_2O_3-MEPCM	Two-step method
Botha et al. [32]	Transformer oil	Silver-silica	One-step method
Suresh et al. [33]	Water	Al_2O_3-Cu	Two-step method
Baghbanzadeh et al. [34]	Water	Silica-MWCNT	Two-step method
Abbasi et al. [35]	Gum Arabic (GA) + water	MWCNT/g-Al_2O_3	Two-step method
Bhosale and Borse [36]	Water	Al_2O_3-CuO	One-step method
Madhesh et al. [37]	Water	Cu-TiO_2	Two-step method
Sundar et al. [38]	Water	MWCNT-Fe_3O_4	Two-step method
Hemmat Esfe et al. [39]	Water	Ag-MgO	Two-step method
Yarmand et al. [40]	Water	GNP-Ag	Two-step method
Afrand et al. [41]	SAE40	SiO_2-MWCNTs	Two-step method
Asadi and Asadi [42]	Engine oil	MWCNT-ZnO	Two-step method
Harandi et al. [44]	EG	F-MWCNTs-Fe_3O_4	Two-step method
Soltani and Akbari [45]	EG	MgO-MWCNT	Two-step method
Yarmand et al. [46]	EG	Biomass carbon-graphene oxide	Two-step method
Selvakumar and Suresh [50]	Water	Al_2O_3-Cu	Two-step method
Han and Rhi [53]	Water	Ag-Al_2O_3	One-step method
Takabi and Shokouhmand [54]	Water	Al_2O_3-Cu	Two-step method
Mechiri et al. [69]	Vegetable oils	Cu-Zn	Two-step method

and utilized to produce nanofluids. The same was done for other different combinations of Ag/HEG/MWNT to form hybrid nanofluids.

Botha et al. [32] prepared nanofluids containing silica using the one-step method. The magnetic stirrer was used to mix the silica to the base fluids at a temperature of 130 °C. Silver nanoparticles supported on silica were prepared correspondingly by mixing the silver nitrate and silica to the base liquid. The oxidation of oil is achieved on high temperature and the reductions of Ag^+ ions to Ag particles by electron transfer reaction, the temperature was thus increased to 130 °C. Suresh et al. [25, 33] synthesized nanocrystalline alumina-copper hybrid (Al_2O_3-Cu) powder by the thermochemical method which consisted of the following stages; (i) spray-drying, (ii) oxidation of precursor powder, and (iii) reduction by hydrogen and homogenisation. The water solution of soluble nitrates of copper and aluminium, $Cu(NO_3)_2 \cdot 3H_2O$ and $Al(NO_3)_3 \cdot 9H_2O$ was prepared with 90:10 of alumina and copper oxide in the powder mixture.

Baghbanzadeh et al. [34] synthesized the hybrid nanostructures using the wet chemical method. Graphitic surfaces of carbon nanotubes were activated in order to achieve synthesis of CNT-based nanohybrid effectively. This is because the graphitic surfaces are chemically inactive. At first, sodium silicate was added to distilled water and then functionalized MWCNTs were added to the previous solution. The new suspension was sonicated by an ultrasonic bath to disperse the suspension with functionalized MWCNTs. CTAB was added to distilled water and dimethylformamide and mixed using a magnetic stirrer. The mixture was then added to the first suspension. After the response, the products were separated and washed by ethanol and distilled water. The gray products were dried in a vacuum oven at 60 °C. Surfactant and impurities were removed from the products. A study by Abbasi et al. [35] used hybrid γ-Al_2O_3/MWCNT hybrid nanofluids. They prepared the hybrid nanofluids using a solvothermal process in ethanol. By completely dissolving aluminium acetate powder in ethanol, the pure MWCNTs and functionalized MWCNTs were added to this suspension. The mixture was then dispersed using an ultrasonic water bath to avoid particle agglomeration. Finally, the mixture was placed under vacuum (50 cm Hg) at room temperature and an ammonia solution was slowly added to the mixture.

Other processes of preparing hybrid nanofluid are presented by Bhosale and Borse [36]. The samples of CuO and Al_2O_3 were mixed in distilled water by adding different concentrations of nanofluids. The number of reading for CHF enhancement was taken to analyse the effect of Nichrome wire size on CHF value. Then the reading for Nichrome wire size and distilled water for different concentrations of Al_2O_3-CuO hybrid nanofluids were taken. Madhesh et al. [37] employed a method involving four steps of facile preparation of the copper/titania hybrid nanocomposite (HyNC) which are: (i) ultrasonic dispersion of an aqueous solution containing titania, (ii) intense stirring and mixing of a copper acetate aqueous solution, containing ascorbic acid and sodium borohydride reducing agents with the prepared titania aqueous solution and ambient pressure for subsequent production of HyNC colloids, (iii) washing and filtration of the HyNC colloids followed by vacuum drying, and (iv) ultrasonic re-dispersion of the prepared HyNC powder into the base fluid for different volume concentrations.

Sundar et al. [38] used an in-situ method to prepare nanocomposite samples. At first, carboxylated-MWCNT was dispersed in distilled water under magnetic stirring. Then, $FeCl^{3+}/FeCl^{2+}$ salts were added in a themolar ratio of 2:1 and stirred. After that, the dispersion of all the iron chlorides was added into the distilled water and simultaneously added to the aqueous sodium hydroxide solution. The solutions were stirred continuously. The reaction is completed once the colour of the solutions turned black. Hemmat Esfe et al. [39] prepared the nanofluid by dispersing nanoparticles into the base fluid. The suspension was stabilized with three methods, which are the addition of surface activators (surfactants), changing the pH value, and using ultrasonic vibrations. XRD was used to determine the size of nanoparticles.

Hemmat Esfe et al. [24] prepared the hybrid nanofluid of Cu/TiO_2–water/EG by the two-step method. Firstly, the nanoparticles were dispersed into different concentrations using a mechanical mixture. The Cu and TiO_2 nanoparticles were mixed using a magnetic stirrer in order to achieve a stable solution of nanofluids. The solution was sonicated using an ultrasonic processor. Consequently, the agglomeration of nanoparticles reduced and prevented the sedimentation in the solution. Yarmand et al. [40] chose the acid treatment for functionalization of graphene nanoplatelets (GNP) hydrophilic. The acid treatment process was conducted by dispersing GNP in a 1:3 ratio of HNO_3 and H_2SO_4 solution under bath-ultrasonication. Next, GNP was washed several times by DI water and then dried in an oven. The solution of ammonia-silver was prepared by adding drop ammonia to silver nitrate solution until fully reacted and the silver colour disappeared. The $Ag(NH_3)_2OH$ solution was mixed into the functionalized GNP solution. The nanofluids were stable and no sedimentations occurred up to 60 days.

Afrand et al. [41] investigated SiO_2-MWCNTs/SAE40 hybrid nanofluid using the two step method. The structural properties of the dry MWCNTs and SiO_2 nanoparticles were measured using X-ray diffraction. The masses of MWCNTs, SiO_2 nanoparticles and engine oil were determined by a sensitive electronic balance. Then, the nanoparticles were dispersed in the oil and allowed to mix with a magnetic stirrer. The suspension was then proceeded using an ultrasonic processor to achieve stable condition. The nanofluids were observed to have good stability and no sedimentation occurred. The same process was repeated for Fe_3O_4–Ag/EG hybrid nanofluids by Afrand et al. [41]. Asadi and Asadi [42] also used the two-step method in their study of MWCNT/ZnO–oil hybrid nanofluid. After dispersing nanoparticles into various volume fractions, the MWCNT and ZnO nanoparticles were mixed in the base fluid using a magnetic stirrer to obtain stable nanofluids. The suspension was inserted into an ultrasonic processor to achieve a superb dispersion and to breakdown the agglomeration of nanoparticles.

Ramachandran et al. [43] employed the two step method to prepare the hybrid nanofluid. They used Al_2O_3 and CuO nanoparticles and dispersed in a base fluid of deionized water. In order to achieve the stability of nanofluids, it was sonicated in an ultrasonic processor. Another researcher that used the two step method was Harandi et al. [44]. The dry *f*-MWCNTs and Fe_3O_4 nanoparticles were mixed in equal volumes. This mixture was dispersed in ethylene glycol with solid volume fractions. In order to attain a characterization of the sample, the structural properties of dry MWCNTs and Fe_3O_4 nanoparticles were measured using X-ray diffraction. To accomplish an appropriate dispersion, after magnetic stirring, every sample went through a sonication process. All specimens prepared were perceived to have good stability and no sedimentation was seen in the time before the analysis.

Soltani and Akbari [45] prepared hybrid nanofluids with ethylene glycol as the base fluid. The mixing process was first implemented using a magnetic stirrer to mix the MgO-MWCNTs/EG into the base fluid. The suspensions then went through the sonication process using an ultrasonic processor to breakdown the agglomeration between the particles and to achieve a stable suspension. The pH measurement using the pH meter was also used as an indicator of the nanofluid stability. In a study by Yarmand et al. [46], the graphene oxide (GO) was dispersed in distilled water by sonication. GO and carbon samples were independently added to aqueous KOH solution. The mass ratio of KOH/carbon and KOH/GO was 4:1. The carbon sample and GO sample were combined, stirred and dried at 50 °C. The mixture was placed in a ceramic boat and kept in a heater tube. The mixture was heated and the obtained nanocomposite was washed with distilled water and HCl a few times to evacuate the impurities and then dried at a temperature of 60 °C. This sample was known as activate carbon/graphene (ACG) and used to make nanofluids.

2.2. Stability, characterization and instrumentations

Nanoparticles are often hydrophobic and therefore cannot typically be dispersed in most heat transfer fluids such as water or ethylene glycol without surface treatments, dispersants or surfactants [47,48].

Furthermore, without these special treatments, the nanoparticles would most certainly agglomerate, thereby creating other problems such as channel clogging and reduction in thermal conductivity of the mixture [14]. Surfactants or dispersion agents are therefore commonly used in nanofluids. Although they are beneficial for stabilizing the suspension, they may also create certain problems for heat transfer mediums. There are three effective methods for stabilizing the suspension namely (i) addition of surface activators (surfactants), (ii) control of the pH value, and (iii) use of ultrasonic vibrations [39,49].

In order to stabilize the hybrid nanofluids, the specific equipment and established approaches for stability were used for dispersing the hybrid nanofluids in base fluids. The main reason for hybrid nanofluids to achieve a stable suspension is to avoid agglomeration and sedimentation. Zeta potential, spectrometer, diffractometer, ultrasonic bath and pH meter are some examples of stability instruments and approaches that were used by many [12,24,25,27,29,32–35,37,39–42,44–46,50,51]. Since the particle size of nanofluids are very small with less than 100 nm, FESEM and SEM analysis were done by several researchers in literatures [12,27,29,32,35,37,40,46,50–52]. The surface and characteristics morphology were seen with these analyses where the size of nanoparticles were defined. Various analysts have considered and reported the types of equipment for measuring the thermal conductivity, density, viscosity and specific heat of the hybrid nanofluids. Understanding the physical and thermal properties of nanofluid is vital before utilizing hybrid nanofluids as a part of practical applications. There are a few well-known imperative types of equipment for nanofluid's thermo-physical properties evaluation, which are commonly used by various researchers.

Various researchers measured the thermal conductivity of hybrid nanofluids using a KD2 Pro thermal properties analyzer [24,25,33,35,39,40,44,46]. The KD2 Pro is a battery-worked, menu-driven device that measures thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity. It comprises a handheld microcontroller and sensor needles that contained both a heating component and a thermistor. The controller module contains a battery, a 16-bit microcontroller/AD converter, and force control hardware. The sensor needle utilized was KS-1, which is made of stainless steel with a length of 60 mm and a diameter of 1.3 mm and nearly approximating the interminable line heat source which gives minimum aggravation to the specimen during each measurement that takes 90 s/cycle. The KD2 Pro thermal property analyzer was used by Baby and Ramaprabhu [12] and Selvakumar and Suresh [50] in their thermal conductivity measurements. The test sensor utilized for these estimations was 6 cm long and 1.3 mm in distance across. In consideration of the temperature impact on the thermal conductivity of the nanofluids, a thermostat bath was utilized. In another paper, Madhesh et al. [37] used the NanoFlash equipment for the measurement of thermal conductivity of hybrid nanofluids. The precision of the equipment was ±3% and the range of thermal conductivity estimation varied from 0.1 W/m K to 2000 W/m K.

Viscosity is another important parameter of thermo-physical properties of hybrid nanofluids. The investigations were done by various researchers as stated in previously published literature [25,33,39,41,45]. The viscosity of the nanofluids was measured using the Brookfield cone and plate viscometer (LVDV-I PRIME C/P) equipped with a 2.4 cm 0.8° cone. The cone is associated with the shaft drive while the plate is mounted in the sample container. The shaft utilized was CPE-40, which can be utilized for tests as a part of the viscosity range of 0.3–1028 cP. A gap of 0.013 mm between the cone and the plate is considered during the measurements. As the shaft is turned, the thick drag of the fluids against the axle is measured by the diversion of the aligned spring. The axle speed accessible with this viscometer falls in the range of 0 to 100 rpm and the shear rate is 0 to 750 s^{-1}. With a specific end goal to guarantee the precision of the estimations, the viscosity was recorded again by (i) taking the same amount of fluid specimen (0.5 to 2 ml), (ii) keeping up the same torque required to turn the shaft (10 to 100% for all paces of pivots) and (iii) keeping up a unistructure gap of 0.013 mm between the cone and the plate inside on which the test fluids are set (utilizing the electronic gap modifying highlight expert provided with the viscometer). Furthermore, Yarmand et al. [46] used a rheometer (Physica MCR, Anton Paar) in measuring the viscosity of EG and ACG/EG hybrid nanofluids. The rotational rheometer comprises a moving tube shaped plate and a stationary barrel shaped surface, which are parallel with a small gap.

A different viscometer (Viscometer, CAP 2000+) was used by Afrand et al. [41] and Asadi and Asadi [42] to measure the viscosity of the hybrid nanofluids. The viscometer was set at medium to high shear rate instrument with Cone Plate geometry and coordinated temperature control of the test material. The measurements were performed at the shear rate scope of 667 to 6667 s^{-1}. The scope of exactness and repeatability of the viscometer were respectively ±2.0% and ±0.5% of the full scale consistency territory. Prior to the estimations, the viscometer was aligned with the motor oil (SAE40) at room temperature. All measurements were repeated at various shear rates for every volume concentration and temperature to ensure the consistency in reading. In the density evaluation of hybrid nanofluids, Yarmand et al. [46] measured the densities of EG and hybrid nanofluids with the Mettler Toledo DE-40 density meter. The precision of density estimation is 0.0001 g/cm^3. For each temperature and test sample, the estimations were recorded three times. For evaluation of specific heat, Yarmand et al. [46] measured the specific heat of the base liquid and the hybrid nanofluids using a differential scanning calorimeter (DSC 8000, Perkin Elmer) with a precision of ±1.0%. The summary of stability, characterization, thermo-physical properties and instrumentations of hybrid nanofluids are shown in Table 2.

2.3. Development and current progress

The parameter studies are related to hybrid nanofluids with base fluids of water and ethylene glycol, whereas the hybrid nanolubricants with base of oil are summarized in Table 3. The development of hybrid nanofluids is classified according to the type of the base fluids. Most research is concerned on the temperature variation in their study and followed by the effect of mass and volume concentrations. Table 3 provides the summaries of the literature for the hybrid research. Water based hybrid nanofluids are mostly used in previous studies [25,29–31,33,36,37,39,40,50,52–54]. The range of temperature that has been used for water based hybrid nanofluids was less than 45 °C with volume and mass concentrations of not more than 2.5% and 50 wt.%, respectively. However, an investigation of gum Arabic (GA) with water based hybrid nanofluids was performed by Abbasi et al. [35]. They conducted the experiment for temperature of 60 °C and 0.1% volume concentration. In other papers, Afrand et al. [41], Harandi et al. [44], and Soltani and Akbari [45] used ethylene glycol as a base fluid with the temperature range of 25 to 60 °C and volume concentrations of up to 2.3%. The combination of water-EG base fluids with the temperature range of 30 to 60 °C and volume concentration of 0.1 to 2% was provided by Hemmat Esfe et al. [24]. For hybrid nanolubricants, the investigation at high boiling points up to 130 °C for transformer and engine oil (SAE40) based was undertaken by Botha et al. [32], Afrand et al. [41], and Asadi and Asadi [42]. They considered volume and mass concentrations of not more than 1% and 4.4 wt.% respectively.

3. Thermo-physical properties of hybrid nanofluids

A study was done by Jana et al. [29] for the nanofluids with AuNPs with only a fixed volume fraction of AuNP was added to water in order to measure the thermal conductivity behaviour. To observe the impact of CNTs on thermal conductivity of AuNP suspensions, CNTs in various concentrations were added to AuNP suspensions. The findings from the study showed that the nanofluids with 1.4% volume concentration of AuNP colloids demonstrated a 37% improvement in thermal conductivity over water. The expansion of CNTs to AuNP nanofluids by 1.4%

Table 2
Summary of stability, characterization, thermo-physical properties and instrumentations of hybrid nanofluids/nanolubricants.

Instruments	Type/model	Measurement	Authors
Stability			
Spectrophoto-meter	UV-Vis-NIR/Cary 500 UV-Vis-NIR/ESCALAB-MKII/Bruker FT-IR/WITEC Alpha 300/Perkin-Elmer 330	Stability	[12,27,29,32,51]
Diffractometer	PANalytical X'PERT Pro X-ray/Bruker AXS D8 Advance/JCPDS (Joint Committee on Powder Diffraction Standards)/X-ray diffractometer (XRD, EMPYREAN, PANALYTICAL)/X-ray diffractometer (XRD, EMPYREAN, PANALYTICAL)	Powder X-ray diffraction (XRD)/XRD spectra/cubical nanoparticles	[12,25,32,33,40,46,50]
Ultrasonic	A Bransonic Ultrasonic Cleaner 1510/Ultrasonic vibrator/Ultrasonic processor (20 kHz, 1200 W, Topsonic)/Ultrasonic bath (DaeRyun Science Inc.)/ Ultrasonic processor (Hielscher Company)	Nanoparticles dispersion/ Ultrasonic pulses/Break down the agglomeration/phase compositions	[24,25,29,30,34,35,37,40–42,44,45,52,53]
pH meter	HANNA, HI 83141/Deep Vision: Model 111/101	pH value	[25,45]
Spectroscopy	Energy-dispersive X-ray (EDX)	Composition	[35,37]
Characterization			
SEM/FESEM	A XL30 ESEM/OXFORD ISIS/FESEM, FEI QUANTA/Hitachi H 800/JSM 6390LV/High resolution SUPRA 55, Carl Zeiss, Electron high tension (EHT): 20 kV/SU8000, Hitachi	Optical spectra/average size	[12,27,32,37,40,46,50–52]
TEM	JEOL TEM-2010F/JEOL 1200 EX/HT 7700, Hitachi machine/High resolution TEM	Optical spectra/average size/microstructure/surface morphology	[12,27,29,32,35,40,46,51,52]
Thermo-physical properties			
Density meter	model DA-505, Kyoto Electronics Manufacturing Co./Anton Paar/Mettler Toledo DE-40	Density	[30,40,52]
Thermal conductivity property analyzer	KD2 Pro Thermal Analyzer Decagon Devices Inc./NETZSCH LFA 447 NanoFlash/AB 200, Fisher scientific	Thermal conductivity	[12,24,25,30,33–35,37,39,40,44,46,50]
Viscometer	Brookfield cone and plate viscometer (LVDV-I PRIME C/P)/Rotational viscometer (Brookfield DV-II + Pro)/ETC Bohlin/Rheometer (Physica, MCR, Anton Paar)/CAP 2000	Viscosity	[25,30,33,37,40–42,45,46,50,52]

AuNP colloid does not indicate a clear change of thermal conductivity. A CuNP–CNT hybrid nanofluid was set up with a fixed amount of CNTs and various CuNP concentrations to measure the impact on thermal conductivity of the suspensions. CNTs did not increase the thermal conductivity of the CuNP–CNT nanofluid but instead brought down the qualities when contrasted with the thermal conductivity of separate single CuNP nanofluids. Indeed, even with the increased measures of the CuNPs in CuNP–CNT suspension, thermal conductivity declines

Table 3
Summary of development and current progress for hybrid research work.

Authors	Nanofluids	Temperature range (°C)	Volume concentration (%)	Mass concentration (wt.%)
Hemmat Esfe et al. [24]	Cu-TiO_2/water-EG	30–60	0.1, 0.2, 0.4, 0.8, 1.0, 1.5, 2.0	–
Suresh et al. [25]	Al_2O_3-Cu/water	40	0.1	–
Jana et al. [29]	CNT-CuNP/water and CNT-AuNP/ water	25	CNT: 0.2, 0.3, 0.5, 0.8 AuNP: 1.5–2.5 CuNP: 0.05, 0.1,0.2, 0.3	–
Ho et al. [30]	Al_2O_3-MEPCM/water	25–40	-	PCM: 2, 5, and 10 MEPCM: 3.7,9.1, and 18.2 Al_2O_3: 2–10
Ho et al. [31]	Al_2O_3-MEPCM/water	<40	–	PCM: 2, 5, and 10 MEPCM: 2–10
Botha et al. [32]	Silver-silica/transformer oil	130	–	Silica: 0.07 to 4.4 Silver: 0.1 to 0.6
Suresh et al. [33]	Al_2O_3-Cu/water	–	0.1, 0.33, 0.75, 1, 2	–
Abbasi et al. [35]	MWCNT + γ-Al_2O_3/gum Arabic + water	60	0.1	–
Bhosale and Borse [36]	Al_2O_3-CuO/water	<40	0.25, 0.5 and 1	–
Madhesh et al. [37]	Cu-TiO_2/water	45	0.1 to 2.0	–
Hemmat Esfe et al. [39]	Ag-MgO/water	–	0 to 2	50:50
Yarmand et al. [40]	GNP-Ag/water	<45	–	0.02, 0.06 and 0.1
Afrand et al. [41]	SiO_2-MWCNT/engine oil (SAE40)	25–60	0.0625, 0.125, 0.25, 0.5, 0.75 and 1.0	–
Afrand et al. [41]	Fe_3O_4-Ag/EG	25–50	0.0375, 0.075, 0.15, 0.3, 0.6 and 1.2	–
Asadi and Asadi [42]	MWCNT-ZnO/engine oil	5–55	0.125, 0.25, 0.5, 0.75 and 1	–
Harandi et al. [44]	*f*-MWCNTs-Fe_3O_4/EG	25–50	0.1, 0.25, 0.45, 0.8, 1.25, 1.8 and 2.3	–
Soltani and Akbari [45]	MgO-MWCNT/EG	30–60	0.1, 0.2, 0.4, 0.8 and 1	–
Selvakumar and Suresh [50]	Al_2O_3-Cu/water	–	0.1	–
Baghbanzadeh et al. [52]	Silica-MWCNT/water	20	–	Hybrid 1: 80:20 Hybrid 2: 50:50
Han and Rhi [53]	Ag-Al_2O_3/water	1, 10, 20	0.005, 0.05, 0.1	–
Takabi and Shokouhmand [54]	Al_2O_3-Cu/water	–	0 to 2	–

and standard deviation increases. The same phenomena were additionally found in AuNP–CNT suspensions.

Ho et al. [30] compared the effect of dispersing Al_2O_3 nanoparticles with a pure PCM suspension. The thermal conductivity of hybrid suspension was increased with the nanoparticle mass fractions. The relative enhancements of more than 4% and nearly 13% in the thermal conductivity were found for the PCM suspension containing nanoparticles of 2 wt.% and 10 wt.%, respectively. Further, they measured the dynamic viscosity for the hybrid suspensions containing diverse mass fractions of MEPCM nanoparticles at a temperature of 30 °C. For pure Al_2O_3–water nanofluids, the dynamic viscosity enhancement showed a marginal increase with the mass fraction of the nanoparticles contrasted with that of pure water while the pure PCM suspensions turn out to be fundamentally improved. Scattering the nanoparticles in the PCM suspension has a tendency to further increase of the compelling element thickness of the hybrid suspension. Specifically, the crossover suspension of PCM at 10 wt.% shows a relative increment of more than three times in the dynamic viscosity compared to water when the fraction of nanoparticles is increased up to 10 wt.%.

Baby and Ramaprabhu [12] found that the thermal conductivity of nanofluids compared to DI water increased with increasing volume fraction. The rate improvement in thermal conductivity was ascertained utilizing the relation of $((k-k_0)\times 100)/k_0$, where 'k_0' is the thermal conductivity of base liquid and 'k' is that of nanofluids. The enhancements in thermal conductivity for volume concentrations of 0.005% and 0.05% are up to 9% and 20%, respectively. The thermal conductivity of the nanofluids also increased with increasing temperature. For 0.005% volume concentration, the increments of thermal conductivity were 9% and 12% respectively at temperatures of 30 °C and 50 °C. Meanwhile for 0.05% volume concentration, the enhancements of thermal conductivity were 20% and 80% at temperatures of 30 °C and 50 °C, respectively. A comparable pattern is displayed for all volume concentrations.

The investigation by Botha et al. [32] was concerned on the thermal conductivity of silica with concentrations extending from 0.07 to 4.4 wt.%. They obtained 1.7% increase in thermal conductivity for 0.5 wt.% silica and a 3.5% increment for 1.8 wt.% concentration of silica alone, without the existence of silver (Ag) nanoparticles in the oil base. The highest concentration of silica under their investigation was 4.4 wt.% with 5.2% enhancement in thermal conductivity. At the point when Ag was upheld on silica, the thermal conductivity was found to increase with an increment in Ag concentration. A thermal conductivity increment of 15% was found when just 0.60 wt.% Ag was supported on 0.07 wt.% silica in the hybrid solution. It is believed that the Ag nanoparticles should be sufficiently close for thermal transport to occur among them and supporting the particles on a reasonable backing gives great grounds to a steady heat transfer system.

Suresh et al. [33] conducted an investigation of thermal conductivity for Al_2O_3–Cu/water hybrid nanofluids, measured at an interval of 15 min for a time of around 3 h after sonication. Fifteen minutes was given between progressive estimations for the temperature of the sensor needle and test to re-equilibrate. The thermal conductivity improvements of Al_2O_3–Cu/water hybrid nanofluids were 1.47%, 3.27%, 6.22%, 7.53%, and 12.11%, respectively for volume concentrations of 0.1%, 0.33%, 0.75%, 1% and 2%, respectively contrasted with deionized water. Thermal conductivity improvements of the hybrid nanofluids were also compared with the alumina/water nanofluids. The enhancements shown for alumina nanofluids were 0.5%, 1.31%, 3.27%, 5.36%, and 7.56%, respectively for the same concentrations. This implies that there is an extremely significant improvement in the effective thermal conductivity because of the hybridisation of alumina nanoparticles utilizing metallic copper particles.

Baghbanzadeh et al. [34] found that the thermal conductivity of nanofluids is improved with the increase in concentration of nanomaterials, and substantial improvement in the case of MWCNTs. Silica nanofluids demonstrated a minimum increment and the improvement in effective thermal conductivity of hybrid nanofluids is within the value between the upgrade of MWCNT and silica nanofluids. Normally, solids have a more prominent thermal conductivity than fluids. The mixture with increased MWCNTs has expanded thermal conductivity of distilled water compared to the other hybrids. An explanation behind this phenomenon is that the impact of carbon nanotube concentrations inside the nanofluids implies that by increasing the amount of carbon nanotubes inside the liquid, more space within the fluids would be occupied by them and more effective networks of nanomaterials would be produced inside the liquid. The summary of thermal conductivity and viscosity of hybrid nanofluid obtained by various investigators are shown in Table 4.

4. Thermo-physical properties of hybrid nanolubricants

Asadi et al. [55] had studied MWCNT/MgO/SAE50 hybrid nanolubricants in volume concentrations of 0.25%, 0.5%, 0.75%, 1.0%, 1.5% and 2.0% of MCWNT and MgO nanoparticles with ratios of 20% and 80%, respectively. Results showed that the dynamic viscosity of hybrid nanolubricants decreased with the increase of temperature but increased with the increase of volume concentration. They also found that the dynamic viscosity of 2.0% MWCNT/MgO/SAE50 hybrid nanolubricants at 40 °C increased up to 65% compared to the base fluid. They also concluded that hybrid nanolubricants in their study were identified as Newtonian fluids under the investigated conditions.

Hemmat Esfe et al. [56] investigated the effects of temperature and concentration on the rheological behaviours of MCWNTs/SiO_2/SAE40 hybrid nanolubricants for 0 to 2.0% volume concentrations containing 20% volume of MCWNTs and 80% volume of SiO_2 in the temperature ranges of 25 to 50 °C. In their study, they observed that for volume concentration up to 1%, the hybrid nanolubricants showed Newtonian behaviour, and non-Newtonian behaviour for volume concentrations higher than 1%. The measurement of viscosity showed that the viscosity decreased with increasing temperature and rose with an increase in the volume concentrations. A new empirical correlation to predict the dynamic viscosity of MCWNTs/SiO_2/SAE40 hybrid nanolubricants was developed.

Afrand et al. [41] studied the effects of temperature and volume concentrations on viscosity of SiO_2/MWCNTs/SAE40 hybrid nanofluids as a coolant and lubricant in heat engines. The SiO_2/ MWCNTs hybrid nanolubricants of volume fractions in the range of 0 to 1.0% were tested to determine the dynamic viscosity of the samples. They also found that the maximum enhancement of viscosity for SiO_2/MWCNT/SAE40 hybrid nanolubricants was 37.4%.

In another study, Hemmat Esfe et al. [57] performed an examination on the rheological behaviours of MWCNTs/ZnO/SAE40. The volume concentrations studied were 0 to 1.0% of MCWNTs and ZnO nanoparticles with ratios of 10% and 90%, respectively. According to their results, the hybrid nanolubricants in this study behaved as Newtonian fluid under the studied temperatures and volume concentrations. Viscosity measurements showed that viscosity decreased with increasing temperature and increased with increments in the volume concentrations. They reported an enhancement of 33.3% for viscosity of engine oil (SAE40) with addition of MWCNTs and ZnO at 1.0% volume concentration.

Dardan et al. [58] investigated the effects of suspending hybrid nanoadditives on the rheological behaviours of engine oil and pumping power of Al_2O_3/MWCNT/SAE40 for 0.0625 to 1.0% volume concentrations. The Al_2O_3 and MWCNT nanoparticles were dispersed in ratios of 75% and 25%, respectively. The viscosity of the hybrid nanofluid increased up to 46% with increasing nanoadditive concentration and decreasing temperature. All hybrid nanolubricant samples showed Newtonian behaviour at all considered temperatures. A correlation to predict the viscosity of Al_2O_3/MCWNTs/SAE40 hybrid nanolubricants was also proposed. The studies related to thermo-physical properties of hybrid nanolubricants are summarized in Table 5.

Table 4
Summary of thermal conductivity and viscosity measurements of hybrid nanofluids.

Authors	Nanofluids	Properties	Findings
Baby and Ramaprabhu [12]	MWNT-HEG/water and MWNT-HEG/EG	Thermal conductivity	Thermal conductivity enhancement of 20% for a volume concentration of 0.05% whereas 289% enhancement of heat transfer coefficient (HTC) for 0.01% volume concentration of *f*-MWNT + *f*-HEG.
Hemmat Esfe et al. [24]	Cu-TiO_2/water and Cu-TiO_2/EG	Thermal conductivity	The ANN model showed better performance in predicting the thermal conductivity of the nanofluid.
Jana et al. [29]	CNT-CuNP/water and CNT-AuNP/water	Thermal conductivity	Thermal conductivity of CNT, CuNP, and AuNP nanofluids higher then hybrid nanofluids.
Ho et al. [30]	Al_2O_3-MEPCM/water	Thermal conductivity, dynamic viscosity	Enhancement of thermal conductivity of PCM suspension with Al_2O_3 nanoparticle dispersion relative to pure water. The dynamic viscosity of the hybrid suspension drastically increased.
Botha et al. [32]	Silver-Silica/Transformer oil	Thermal conductivity	Thermal conductivity was increased with the increasing of silver concentrations.
Suresh et al. [33]	Al_2O_3-Cu/water	Thermal conductivity, viscosity	Viscosity increment is substantially higher than the increase in thermal conductivity.
Baghbanzadeh et al. [34]	Silica-MWCNT/water	Thermal conductivity	Effective thermal conductivity of nanofluids increased with the addition of nanomaterials concentration.
Abbasi et al. [35]	MWCNT + γ-Al_2O_3/gum Arabic (GA) + water	Thermal conductivity	The enhancement in thermal conductivity reached up to 20.68% at 0.1% volume concentration of hybrid nanofluids.
Hemmat Esfe et al. [39]	Ag–MgO/water	Thermal conductivity	Thermal conductivity and dynamic viscosity of nanofluid increased for hybrid nanofluids.
Afrand et al. [41]	SiO_2-MWCNTs/SAE40	Dynamic viscosity	The dynamic viscosity enhanced with an increase in the solid volume fraction and decreases with increasing temperature. The results indicated that the maximum enhancement of hybrid nanofluid viscosity up to 37.4%.
Asadi and Asadi [42]	MWCNT/ZnO-engine oil	Dynamic viscosity	Dynamic viscosity of the nanofluid decreased with the increasing temperature by 85%. In addition, the dynamic viscosity increased with the volume concentration and enhanced by 45%.
Harandi et al. [44]	*f*-MWCNTs-Fe_3O_4/EG	Thermal conductivity	The maximum enhancement of thermal conductivity of nanofluid was 30% for temperature of 50 °C and the volume concentration of 2.3%.
Soltani and Akbari [45]	MgO-MWCNT/ethylene glycol	Dynamic viscosity	The dynamic viscosity increased with increasing volume concentration and decreased with the rising temperature. The relative viscosity revealed that when the volume concentration enhanced from 0.1 to 1%, the dynamic viscosity increased up to 168%.
Yarmand et al. [46]	Biomass carbon-graphene oxide/EG	Thermal conductivity	Thermal conductivity of activate carbon/graphene (ACG) dispersed in EG based nanofluid showed an enhancement of 6.5% at 40 °C and weight concentration of 0.06%.
Mechiri et al. [69]	Cu-Zn/vegetable oils	Thermal conductivity	Thermal conductivity of nanofluid increased with increasing hybrid nanoparticle loading and temperature.

5. Heat transfer performance

Performance of hybrid nanofluids has been summarized from previous research [31,37,38,43,59–62]. The performance of hybrid nanofluids is classified into two groups. The first group concerns research on the heat transfer observations and the other concerns the pressure drop and friction factor. Table 6 provides summary on heat transfer performance of hybrid nanofluids.

Baby and Ramaprabhu [12] investigated the heat transfer evaluation and directed for various volume concentrations of hybrid *f*-MWNT/*f*-HEG dispersed in water based nanofluids for various Reynolds numbers. For water based nanofluids, the Reynolds numbers were utilized for 4500, 8700 and 15,500, which modelled the turbulent stream. The analyses focused on constant heat flux boundary conditions. The volume concentrations of 0.005% and 0.01% were used in their study. At the entrance of the test section, the improvement in the heat transfer coefficient is observed to be 181% and 264%, respectively for 0.005% and 0.01% concentrations for Reynolds number of 4500. Towards the end of the test section, the enhancements in heat transfer were improved further with 166% and 206% respectively for the same volume concentrations and Reynolds number. The heat transfer enhancement at high Reynolds number is observed to be higher than low Reynolds number measured at both the entrance and exit of the test sections. Though for EG based liquids, the heat transfer coefficient increased with increase of the volume concentrations and Reynolds numbers.

In another paper, the Nusselt numbers for Al_2O_3-Cu hybrid nanofluids were obtained by utilizing the normal temperature of the wall, average bulk temperature, and the actual heat flux value [26]. They stated that the velocity profile decreased with a distinction between the normal tube wall temperature and the mass mean temperature of nanofluids. Consequently, it improved the heat transfer coefficient which resulted with a high Nusselt number. The rate of heat transfer was improved for hybrid nanofluids in contrast with water and Al_2O_3/water nanofluids numerically. The convective heat

Table 5
Studies related to thermo-physical properties of hybrid nanolubricants.

Author(s)	Base fluid	Dispersed particles	Hybrid ratio	Volume concentration (%)	Remarks
Afrand et al. [41]	Engine oil (SAE40)	MWCNT-SiO_2	–	0.0625–1.0	Dynamic viscosity enhanced with an increased in the volume concentration and decreased with increasing temperature.
Asadi et al. [55]	Engine oil (SAE50)	MWCNT-MgO	20/80	0.25–2.0	Dynamic viscosity decreased with the increasing of temperature.
Hemmat Esfe et al. [56]	Engine oil (SAE40)	MWCNT-SiO_2	20/80	up to 2.0	Viscosity measurements showed that the viscosity decreased with increasing temperature and rose with an increased in the volume concentration.
Hemmat Esfe et al. [57]	Engine oil (SAE40)	MWCNT-ZnO	10/90	up to 1.0	Viscosity measurements showed that the viscosity decreased with increasing temperature and increased with an enhancement in the volume concentration.
Dardan et al. [58]	Engine oil (SAE40)	Al_2O_3-MWCNT	75/25	0.0625–1.0	Viscosity of the hybrid nanofluids increased with increasing nanoadditives concentration and decreasing with the temperature.

Table 6
Summary of heat transfer performance and pressure drop of hybrid nanofluids.

Authors	Nanofluids	Findings
Heat Transfer Observation		
Baby and Ramaprabhu [12]	MWNT-HEG/water and MWNT-HEG/EG	The heat transfer coefficient (HTC) increased with an increasing of volume concentration. The 0.01% volume concentration showed the highest HTC.
Suresh et al. [25]	Al_2O_3-Cu/water	The convective heat transfer showed a maximum enhancement of 13.56% for Nusselt number.
Moghadassi et al. [26]	Al_2O_3-Cu/water-based Al_2O_3	The convective heat transfer coefficient for the hybrid nanofluids is higher than the based fluids and the average Nusselt number was increased by 4.73% and 13.46% compared to Al_2O_3/water and pure water, respectively.
Bhosale and Borse [36]	Al_2O_3-CuO/water	The maximum enhancement of critical heat flux (CHF) was obtained up to 90% for 1% volume concentration and for 36 gauge nichrome wire.
Sundar et al. [38]	MWCNT-Fe_3O_4/water	The enhancement in Nusselt number for 0.1% of MWCNT-Fe_3O_4 hybrid nanofluids was varied from 9.35% to 20.62%, whereas for 0.3% concentration was found from 14.81% to 31.1%.
Yarmand et al. [40]	GNP-Ag/water	Heat transfer performance showed an improvement for hybrid nanofluids compared to the based fluid.
Selvakumar and Suresh [50]	Al_2O_3-Cu/water	The convection heat transfer coefficient was increased.
Han and Rhi [53]	Ag-Al_2O_3/water	Thermal resistance was increased with volume concentration.
Takabi and Shokouhmand [54]	Al_2O_3-Cu/water	Hybrid nanofluids was improved the heat transfer rate compared to the pure water and nanofluids.
Nuim Labib et al. [70]	CNT-Al_2O_3/water and CNT-Al_2O_3/EG	Ethylene Glycol based hybrid nanofluids gives better heat transfer enhancement than that of water based hybrid nanofluids.
Pressure drop and friction factor observation		
Ho et al. [31]	Al_2O_3-MEPCM/water	The heat transfer efficiency appeared to be severely outweighed by pressure drop penalty.
Madhesh et al. [37]	Cu-TiO_2/water	The friction factor and pressure drop of hybrid nanocomposite (HyNC) for 2.0% volume concentration were expected to be increased by 1.7% and 14.9% respectively, which implies a penalty in the pumping capacity.
Selvakumar and Suresh [50]	Al_2O_3-Cu/water	The pumping power is increased significantly.
Huang et al. [71]	MWCNT/water + Al_2O_3/water	The pressure drop of the hybrid nanofluids is smaller than the Al_2O_3/water nanofluids.

transfer coefficient for the Al_2O_3-Cu hybrid nanofluids is higher than the base fluids and Al_2O_3/water nanofluids. The average Nusselt number was increased by 4.73% and 13.46% compared to Al_2O_3/water and pure water, respectively. This implies that with an addition of copper nanoparticles, the effective heat transfer rate is increased by 5%.

A study conducted by Sundar et al. [38] found that the Nusselt number increased with the increase of MWCNT-Fe_3O_4 hybrid nanofluid volume concentration and Reynolds number. The enhancement in the Nusselt number for 0.1% volume concentration of the hybrid nanofluids varied from 9.35% to 20.62%. Further, the heat transfer enhancements were noticed for 0.3% volume concentration with 14.81% and 31.10% respectively for the Reynolds numbers of 3000 and 22,000. The Nusselt number improvement for MWCNT-Fe_3O_4 nanofluids is additionally attributed by the molecule Brownian movement, thermo-physical properties of the nanoparticles and extensive surface range. Henceforth, the heat transport capability of MWCNT-Fe_3O_4 nanofluid also increased further. The improvement in the Nusselt number might be credited to the alluring properties of nanofluids with high thermal conductivity and high specific heat, which contrasted with the distilled water.

Suresh et al. [25], Selvakumar and Suresh [50] and Takabi and Shokouhmand [54] studied the impact of convective heat transfer performance of thin-channelled heat sink. They examined the heat transfer by utilizing the Al_2O_3–Cu hybrid nanofluids as the working liquid and deionized water as the base fluids. With the expansion of mass flow rate of the deionized water in the thin-channelled copper heat sink, the convective heat transfer coefficient also increased. Huge expansion in convective heat transfer coefficient has been observed for Al_2O_3–Cu/water hybrid nanofluids contrasted with deionized water. The stated reasons for the improvement in the convective heat transfer coefficients with the utilization of hybrid nanofluids; (i) the enhancement in thermal transport property of hybrid nanofluids is because of the inclusion of copper and alumina nanoparticles, (ii) nanoparticle thermal dispersion, and (iii) increased energy exchange between the hybrid nanoparticles/DI water and solid surface is because of the narrow channel width.

6. Challenges and applications

Despite the fact that a lot of research has been done on nanofluids over the previous decade and hybrid nanofluids over the past few years, the conclusions on their behaviour, characteristics, and performances remain fairly insufficient. Henceforth, it is important to engage more investigations so as to legitimately measure the impacts of particle size and shapes, sufficient scattering of particles and sedimentation, grouping of particles, surfactant impacts, nanofluid temperatures, and satisfactory experimental systems and techniques. Some of these issues have been addressed in part by a few researchers.

The preparation of homogeneous suspensions remains a specialized test because of extremely solid Van der Waals interactions. To get a stable nanofluid, physical or chemical treatments have been conducted, for example, an increase of surfactant, and surface change of the suspended particles or applying strong force on the groups of the suspended particles. Dispersing agent and surface-dynamic agents have been utilized to scatter the nanoparticles of hydrophobic materials in aqueous solutions [63]. Generally, the long term stability of nanoparticle dispersion is one of the essential necessities of the nanofluid applications. The stability of nanofluids has a decent comparing association with the improvement of thermal conductivity where the better the dispersion conduct, the higher the thermal conductivity of nanofluids [64]. Eastman et al. [65] uncovered that the thermal conductivity of ethylene glycol based nanofluids containing 0.3% copper nanoparticles diminishes with time. In their study, the thermal conductivity of nanofluids was measured twice with the first within 2 days and the second was 2 months after the preparation. It was found that the crisp nanofluids showed marginally higher thermal conductivities than nanofluids that were amassed to 2 months. This may be because of the reducing dispersion stability of nanoparticles with time. Nanoparticles may tend to agglomerate when kept for certain periods of time. Lee and Mudawar [66] investigated the effects of Al_2O_3 nanofluid stability with time. It was found that nanofluids kept for 30 days displayed some settlement contrasted with crisp nanofluids. It demonstrated that long term degradation in the thermal performance of nanofluids could happen. Particle settling must be analysed precisely since it might prompt obstruction of cooling sections.

According to Sidik et al. [67], nanofluid manufacturing has been limited to laboratory-scale productions. High costs will affect at least the near future and limit its potential widespread for applications. Until manufacturing processes allow mass productions of nanoparticles and associated with suspensions, the costs will undoubtedly remain high. As stated by Li et al. [68], numerous research has reported test concentrates on the thermal conductivity of nanofluids. In the last few years, many experimental investigations on the components affecting thermal conductivity of nanofluids, for example, the (i) impact of nanoparticles, (ii) impact of base fluids, and (iii) impact of the liquid–solid interface.

The different uses of nanofluids/nanolubricants have been looked into since decades ago and quantities of review articles have additionally distributed as of late covering commercial, industrial, and transportation applications. Application ranges are generally differed, for example, electronic component cooling, automotive industry, solar energy and refrigeration systems. The hybrid nanofluids/hybrid nanolubricants are a significant new kind of nanofluid and they are still in the innovative work stage, which is similar to their applications in the industry. It is hoped that hybrid nanofluids and hybrid nanolubricants are utilized for comparative applications with better performance.

7. Conclusions

In this paper, an inclusive review on thermo-physical properties of hybrid nanofluids and hybrid nanolubricants was done with comprehensive studies on previous research. The hybrid nanofluids generally can be classified as new groups of nanofluids on which significantly more research studies should be done before their functional applications in the commercial ventures. Their major applications can be in the field of heat transfer applications. This is because of the synergistic impact through which they give ideal properties of the greater part of its constituents. It has been found that the enhanced thermal conductivity of nanofluids is one of the driving components for enhanced execution in various applications. The accentuation of the majority of the studies on hybrid nanofluids and hybrid nanolubricants is mostly focused on stability and thermal conductivity whereas the other thermo-physical properties were disregarded. Thus, many points are still left to be studied in order to test the solidness and other thermo-physical properties of hybrid nanofluids with expectations to commercial it for applications in the industry. The present review discussed in detail and summarized the methods, instrumentations of preparation, developments and current progress of hybrid nanofluids and it thermo-physical properties. The performances in terms of heat transfer, pressure drop and friction factor of hybrid nanofluids are carried out by different researchers. Some reviewed applications of hybrid nanofluids have also been discussed.

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