Journal of Thermal Analysis and Calorimetry (2024) 149:9523–9557
https://doi.org/10.1007/s10973-024-13449-1

An extensive review of preparation, stabilization, and application of single and hybrid nanofluids

Pritam Kumar Das[1] · Apurba Kumar Santra[2] · Ranjan Ganguly[2] · Santosh Kumar Dash[3] · Suresh Muthusamy[4] · MizajShabil Sha[5] · Kishor Kumar Sadasivuni[5,6]

Received: 5 October 2023 / Accepted: 8 July 2024 / Published online: 6 August 2024

Abstract

The researchers attract nanofluids due to their improved thermal and physical properties compared to the base fluid. The colloidal mixture of nanometre-sized particles with conventional fluid is known as nanofluids. Compared with single nanofluids, hybrid nanofluids show better enhancement in thermophysical properties. Combining nanoparticles into the host fluid is called a hybrid nanofluid. The preparation of nanofluid needs more importance. However, the physiochemical properties of the nanofluid mainly depend on the stability of the nanofluid. The article aims to provide detailed information about preparing different types of single and hybrid nanofluids dispersed in various base fluids, preparation techniques, stabilization processes, applications and challenges. Different types of surfactants and characterization methods are suggested to improve the stability of the prepared solution. It was observed that all types of nanoparticles and hybrid nanoparticles could be synthesized with different base fluids with the help of the sonication process, particle-to-surfactant ratio, magnetic stirrer and many more. The two-step method is mostly preferred by the researchers compared to the single-step method to prepare the nanofluid. Application of single and hybrid nanofluids has been highlighted in different areas; few challenges have also been identified and must be checked before implementation in the industry.

Keywords Application and challenges · Different base fluids · Hybrid nanofluids · Preparation and characterization techniques

Introduction

Heating and cooling by the fluid are the most important challenge in industrial application, and it is applied in many areas: cooling of electronic devices [1], solar water heating [2, 3], manufacturing [4], and many more. Heat removal is a major issue for any technology which deals with high power and small size. An electronic device that operates at high speed with high power and heat fluxes requires a high-quality cooling medium. The selection of a convenient heat transfer (HT) fluid for heat dissipation is necessary to design the heat exchanging system. In the last two decades, researchers and scientists have attempted to use conventional fluids (ethylene glycol (EG), water or a mixture of water and EG, kerosene, engine oil (EO), paraffin oil and vegetable oil), but due to the low thermal conductivity (TC) of these fluid is often a matter of concern for industrial application. By improvising the fluid, a new type of fluid was developed, which provides better heating and cooling performance for different thermal systems. Choi [5] invented a new concept of fluid

✉ Suresh Muthusamy
infostosuresh@gmail.com

✉ Kishor Kumar Sadasivuni
kishor_kumars@yahoo.com

[1] Department of Mechanical Engineering, Aditya University, Kakinada, Andhra Pradesh, India

[2] Department of Power Engineering, Jadavpur University, Kolkata, West Bengal, India

[3] Department of Mechanical Engineering, Ghani Khan Choudhury Institute of Engineering and Technology, Narayanpur, Malda, West Bengal, India

[4] Department of Electrical and Electronics Engineering, Kongu Engineering College (Autonomous), Perundurai, Erode, Tamil Nadu, India

[5] Centre for Advanced Materials, Qatar University, Doha, Qatar

[6] Department of Mechanical and Industrial Engineering, Qatar University, PO Box 2713, Doha, Qatar

known as nanofluid has improved its thermal properties and shown great promise in enchanting the indifferent area of HT application. The application of nanofluids appears promising in the future, but the use of nanofluids has shown serious problems which need to be overcome. Few of the applications and challenges of single nanofluids and hybrid nanofluids are demonstrated: Gupta et al. [6] measured the TC of metal oxides (CuO, MgO, Fe_2O_3) with water/EG at different temperatures (30–80 °C) and concentrations (0.05%, 0.1%, 0.2%). They identified that the enhancement in the TC of metal oxide nanofluids as the increment of temperature and concentration. Alfellag et al. [7] investigated the optimal nanoparticle mixing ratio of clove-treated MWCNTs/TiO_2 nanomaterials at a fixed concentration (0.1 mass%). TC and viscosity measurements were done at different temperatures (30–50 °C). They found that ideal mixing ratio with the highest TC and lowest possible viscosity was found to be 60:40 based on the thermophysical performance factor and also identified that hybrid nanofluids shown higher performance than single nanofluids. Bao et al. [8] applied MWCNTs–SiO hybrid nanofluids on direct absorption solar collector and observed that the photothermal conversion efficiency improved (64.7%) by applying the hybrid nanofluid and TC of hybrid nanofluids is also enhanced. Ajeena et al. [9] measured TC of ZrO_2–SiC/DW hybrid nanofluids at different concentrations (0.025–0.1%). They found that TC of hybrid nanofluid enhanced up to 25.75% at concentration of 0.1% and at temperature of 60 °C. Rudyak et al. [10] measured TC of two nanofluids (SWCNTs and MWCNTs) with different host fluids at various concentration (0.01–1.0%). They found that TC of SWCNTs was more than MWCNTs and at a fixed concentration, the TC of nanofluids increased with a decrease in the nanotube length. The challenge of nanofluid includes increases in pressure drop, stability of nanoparticle dispersion for a long period, clogging, high erosion, thermal performance in turbulent flow, troubles in production process, cost of nanoparticles, high viscosity, low specific heat, etc. Most of the experimental studies are to determine the heat transfer coefficient (HTC) of nanofluid based on metallic oxide nanoparticles. Designing a thermal system using a properly prepared stable nanofluid requires the determination of its thermophysical properties, such as viscosity, TC, density and heat capacity. Nanofluids can be applied in various devices and systems, so more studies have been performed to inspect the physical properties of nanofluids. Hybrid nanofluids shows higher TC, chemical stability, mechanical resistance and physical strength compared to their respective base fluids and single nanofluids. So the efficiency of the hybrid nanofluid is better than the single nanofluid. Hybrid nanofluids also reduce drag and transfer heat more efficiently compared to base fluids and single nanofluids. Table 1 shows the difference between single nanofluid and hybrid nanofluid.

This article is demonstrated an extensive literature review of single nanofluid and hybrid nanofluid. The main aim of the present research is to give a detailed review of the preparation of various types of single and hybrid nanofluids. The preparation of nanofluids includes different types of base fluids and surfactants. Different methods of preparation techniques (single/one step method, two step method), processes of stabilization, algorithm of preparation, and characterization of single and hybrid nanofluids are demonstrated. The applications of nanofluids are reviewed and identified the research gaps for the future research. Moreover, a few challenges are identified that researchers must overcome before implementing the industrial application. Hence, acute research is required for the excerpt of convenient hybrid nanoparticles, their preparation, characterization

Table 1 Difference between single and hybrid nanofluids

Single nanofluids	Hybrid nanofluids
A nanofluid is a suspension of nano-sized (1–100 nm) materials (nanoparticles, nanotubes, nanofibres, nanowires, and nanorods) dispersed in conventional fluids	Hybrid nanofluids are advanced nanofluids synthesized by blending more than one nanosized metal, metal oxide, or mixture of both in the conventional fluid to have greater thermophysical properties
Nanoparticles used by the researchers are generally metals: Cu, Al, Ni, and Ag; metal oxides like ZrO_2, TiO_2, Al_2O_3, $BaTiO_3$, Fe_3O_4, CuO, ZnO, SiO_2; and a few other particles such as CNT, SiC, graphene, AlN, and $CaCO_3$. [11]	Hybrid nanofluids are used by different researchers are: Al_2O_3–CNT, Al_2O_3–Cu, Al_2O_3–Ag, Cu–TiO_2, Cu–Cu_2O, Cu–Zn, MWCNT–Fe_3O_4, SWCNT–MgO, MgO–MWCNT, Fe_2O_3–CNT, Fe_3O_4–Graphene, Graphene–Ag, SiO_2-CNT, Ag–TiO_2, Ag–CNT and many more
Nanofluid exhibits higher TC compared to the conventional fluid. It also has a high surface area, which improves HT capabilities	Hybrid nanofluid shows higher TC than single nanofluid so HT will improve
Nanofluid is easy to synthesize, and the nanoparticles can remain suspended in base fluids for longer	Hybrid nanofluids are difficult to synthesize, so the nanoparticles must be selected based on their chemical composition
Reduced pumping power compared to the base fluid to achieve equivalent HT intensification	Simple nanofluids can replace hybrid nanofluids due to their wide absorption range, low extinction, pressure-drop, frictional losses and pumping power compared to the nanofluids
Found to be potentially suitable for many applications such as cooling, biomedical, and defence	The hybrid nanofluids have been used in different HT applications such as heat pipes, heat exchangers, and micro-channels

and long period of stability. Very few research works have been reported regarding this scenario in the literature.

Preparation and stabilization of single and hybrid nanofluids

The most important part of the experimental study on nanofluids is the preparation of stable nanofluids, free from agglomeration and no sedimentation for longer. Two methods were used to prepare nanofluids, i.e.:

- Single/one-step method
- Two-step method

Single/one-step method

Single-step method is a process where the production of nanoparticles and their dispersion in the host fluid occurs simultaneously. Nanoparticles are prepared by the physical vapour deposition (PVD) method, i.e. condensation of the metallic vapour into a flowing low vapour pressure fluid, which is called vacuum evaporation onto a running oil substrate (VEROS) invented by Yatsuya et al. [12]. In this technique, drying processes, dispersion and storage of nanoparticles are not necessary, so the accumulation of nanofluids can be optimized, and nanofluid stability can be increased. Direct Evaporation technique is the modified version of the VEROS technique; in this process, the vapour metal condensed to particles and mixed into the host fluid. This technique provides good control over the particle size and forms stable nanofluids without adding surfactants [13]. The laser ablation (LA) method is another one which has been used to form alumina nanofluids [14]. A pure chemical synthesis method developed copper nanofluid mixed in EG [15].

The advantages of the single-step method are less particle accumulation, enhanced nanofluid stability, drying cost, and averted dispersion. The disadvantages of this method are: residual reactants are left in the nanofluids, due to incompletereaction or stabilization (difficult to remove), difficult to scale it up due to the cost of production,compatible low vapour pressure base fluid [16]. Some other examples of single-step processes are described in Table 2. Figures 1–7 show the image of different types of single-step method innovated by various researchers, such as VEROS, direct evaporation technique, pulsed laser ablation in liquid (PLAL), microwave synthesis, submerged arc nanoparticle synthesis system (SANSS), polyol process, and phase transfer method, respectively.

Table 2 Different types of single-step methods

Types	Materials used	Authors	Remarks
VEROS	Ag, Fe, Co, Ni	[12, 17]	Ultrafine particles were prepared to ensure the particle size was less than 100 Å, the size distribution was very sharp, fine particles are independent of each other because they are dispersed in oil, and the particle yield per unit time is very high
Direct evaporation technique	Cu, $A1_2O_3$	[18, 19]	Great control over nanoparticle size and prepared a stable nanofluid without any additives
Chemical reduction	Cu, Au, Cuprous Oxide	[20–22]	Nanofluids can be synthesized in a short time. Non-agglomerated and stably suspended nanofluids were achieved, and this method is economical
Laser ablation	Ag, CuO, Si, Ti	[23–27]	It is a chemically simple and clean synthesis method. The new phase formation of nanocrystals may involve both liquid and solid
Microwave irradiation	CuO, Cu, $AgNO_3$	[15, 28, 29]	The adoption of microwave irradiation greatly affects the reaction rate and nanofluid properties. This is well known in the food industry and later has found several applications in chemistry, especially in organic
Polyol process	Ag, Metal powders, Ag nanowires,	[30–32]	Coating the hydrophilic polyol over particles, water-based nanofluids were prepared
Submerged arc nanoparticle synthesis system (SANSS)	Ag, Cu	[33, 34]	This system has been developed to synthesize the nanofluids using various dielectric liquids. SANSS is indicated to be effective in averting particle aggregation, produced uniformly distributed and well-controlled in size
Phase-transfer method	Ag, Au, Pt	[35, 36]	Reactant immigrates from one phase to another where the reaction occurs. High stability against hydrolysis and good binding strength for metal ions

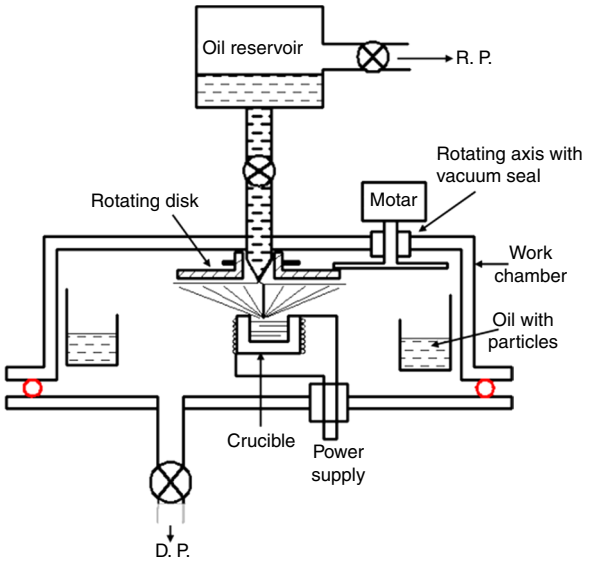

Fig. 1 Schematic diagram of vacuum evaporation onto a running oil substrate method [12]

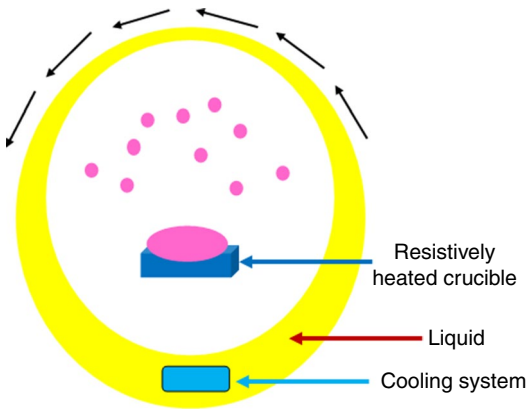

Fig. 2 Schematic diagram of direct evaporation technique [18]

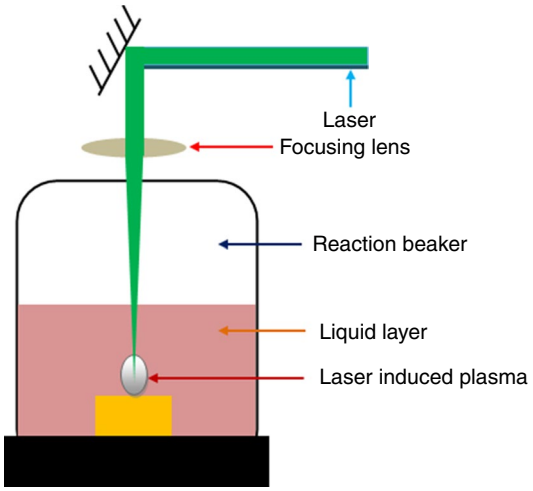

Fig. 3 Schematic diagram of pulsed laser ablation in liquid method [24]

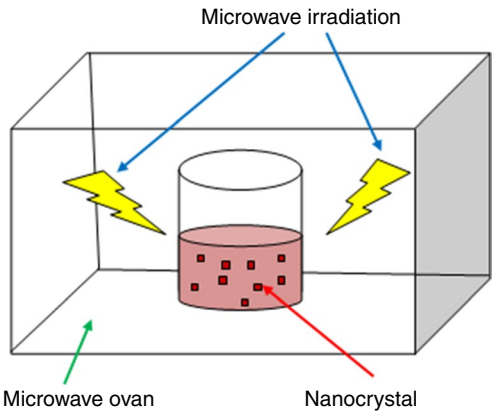

Fig. 4 Schematic diagram of microwave synthesis method [15]

Two-step method

This process is mostly used to prepare single and hybrid nanofluids, employed by several researchers [37, 38]. Initially, the nanoparticles were produced by either chemical (sol–gel and vapour phase methods) or physical (milling, grinding, etc.) processes in dry powder. In the next step, prepared nanoparticles were mixed into base fluid with the help of a mixing device such as an intensive magnetic stirrer [39], high-shear mixing, homogenizer [40], ball milling [41], or by employing ultrasonic devices [42]. Stirring process decreases particle agglomeration and sedimentation [43] because agglomeration is a major problem in preparing nanofluids [44]. Due to large scalability and cost-effectiveness, this method is adopted for

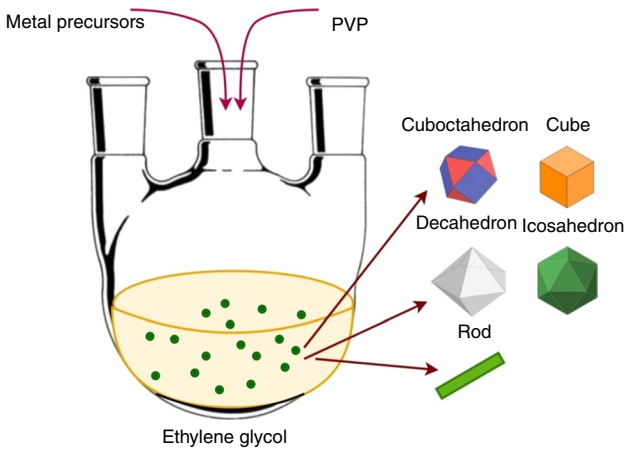

Fig. 5 Schematic diagram of polyol process [31]

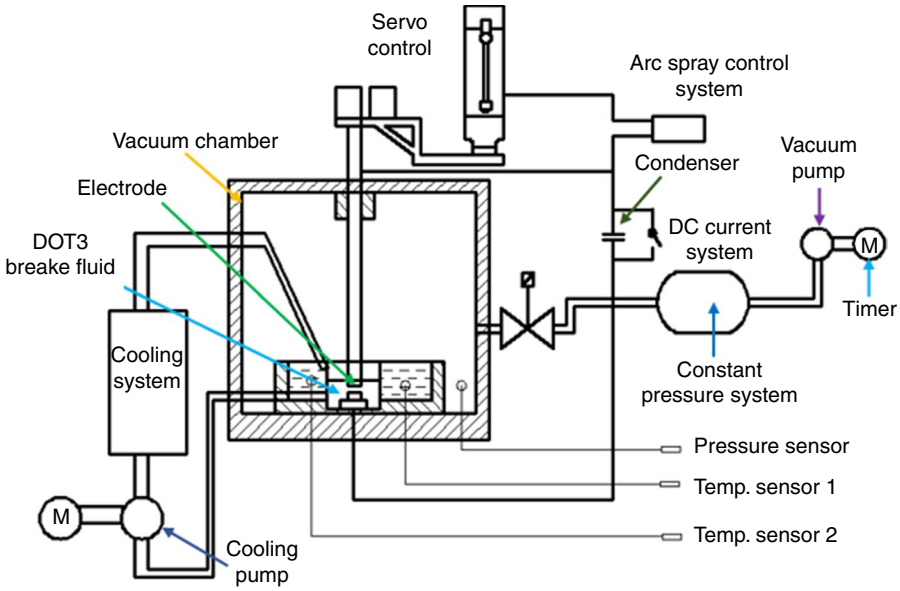

Fig. 6 Schematic diagram of submerged arc nanoparticle synthesis system (SANSS) technique [33]

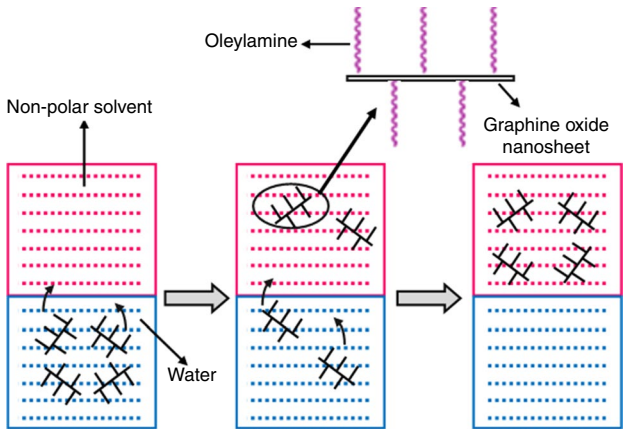

Fig. 7 Schematic diagram of the phase transfer process [35]

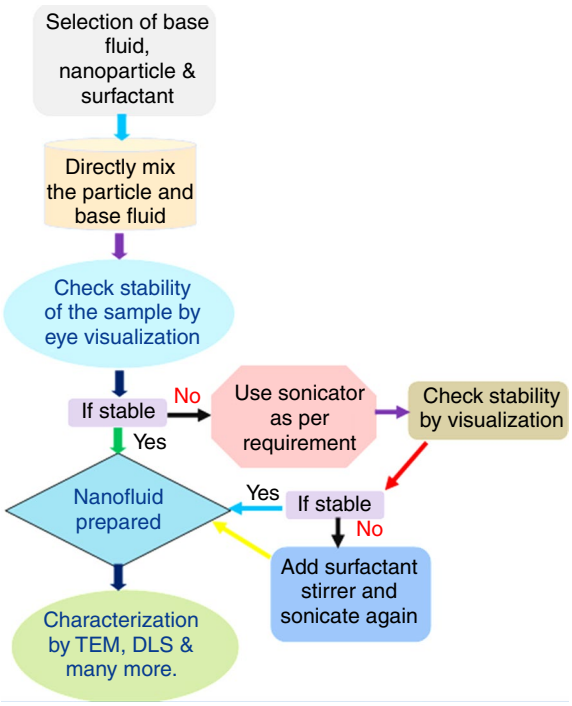

Fig. 8 Algorithm for preparation of nanofluids

preparing the nanofluids. Manna [45] and Eastman et al. [19] suggested that the two-step method is more relevant for preparing nanofluids with oxide nanoparticles than metallic nanoparticles. Nanoparticle tends to aggregate due to its high surface area and surface activity. Therefore, nanoparticles are to be stabilized to prevent agglomeration [46] with the support of sonication. Stability is the main problem for this method, as the nanopowder mixes comfortably due to strong van der Waals force among the particles. Despite this issue, two-step methods are the most economical for preparing nanofluids. The algorithm and nanofluid preparation by the two-step method are described in Figs. 8 and 9, respectively.

Stabilization

Initially, Xuan and Li [47] used the basic method for stabilization of the prepared suspension by (a) altering the pH value of the suspension, (b) employing surfactants and (c) applying ultrasonication. The above methods can modify the surface properties of suspension. The use of this technique of stabilization depends upon the application of nanofluid.

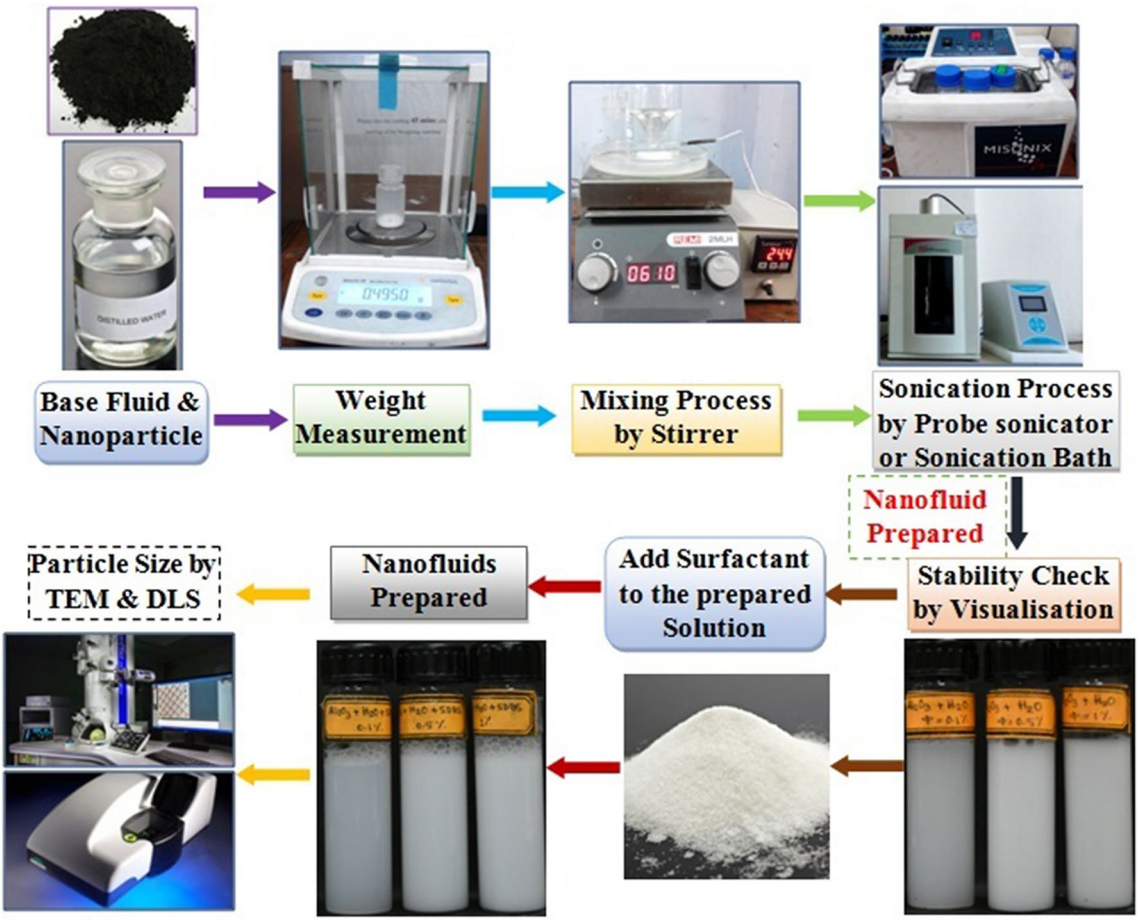

Fig. 9 Nanofluids preparation by two-step method

Table 3 Different types of surfactants

Types of surfactants	Examples
Anionic	Carboxylates, Sulphate, Sulphonates, Phosphate, Petroleum Sulphonates, Ammonium lauryl sulphate, SDBS, Sodium stearate, Sodium laureth sulphate, Potassium lauryl sulphate, Sodium dodecyl sulphate (SDS), Alkyl-benzene-sulphonates, Olefin Sulphonates, Sulphated Esters, Sulphated Alkanolamides, Alkylphenols, and many more
Cationic	Quaternary Ammonium Salts; CTAB, Benzalkonium chloride (BAC), Benzethonium chloride (BZT), Distearyl dimethylammonium chloride, Dioctadecyldimethylammonium bromide (DODAB), Cetylpyridinium chloride (CPC), 2-Alkyl 1-Hydroxethyl 2-Imidazolines, Amines with Amide Linkages, Alicyclic Amines and Polyoxyethylene Alkyl, and many more
Nonionic	Polyoxyethylene glycol, Polyethylene Glycol (PEG), Esters, Ethoxylated Aliphatic Alcohol, Gum arabic (GA), Polyoxyethylene Fatty Acid Amides, Carboxylic Acetic acid (AA), Poly vinyl pyrrolidone (PVP), Stearyl alcohol, Oleic acid (OA), Oleyl amine, Tween 80, Tween X-100, and many more
Amphoteric/zwitterionic	Both cationic and anionic. Sodium lauroamphoacetate, Cocamidopropyl betaine, Lecithin, Hydroxysultaine, Phospholipids phosphatidylserine, Phosphatidylcholine, Sphingomyelins, Phosphatidylethanolamine, etc.

The properties of the solution and particles will decide the selection of surfactants. Surfactants lower the surface tension between two liquids or between a solid and a liquid. Various surfactants are available; it depends on the charge of the head group of surfactants. A few examples of surfactants are mentioned in Table 3.

Preparation of different types of single and hybrid nanofluids

The difference between single and hybrid nanofluids is already explained in Table 1. Hybrid nanomaterial shows exceptional physiochemical properties not present in the single component. A single material may have good thermal and rheological properties but not all favourable characteristics. Several methods were used to prepare hybrid nanofluids, which have been discussed later.

Water-based single nanofluids

Researchers and scientists mostly used water for preparing the single nanofluids. A few of the examples are described here. Kathiravan et al. [48] prepared Cu nanoparticles (size of 10 nm) by sputtering method. Different nanofluids were prepared with water and water with 9.0% surfactant (SDS) and sonicated in an ultrasonicator for about 10 h. Few particles were found to agglomerate and form clusters after 10 h of ultrasonication. Kole and Dey [49] prepared stable Cu (40 nm)–water nanofluids by ultrasonication (power at 200 W) and followed by a magnetic stirring process (10 h) without using any surfactant. The suspension stability of Cu–water nanofluid was stable for more than two weeks without any sedimentation. Still, due to the small cluster formation, the average diameter was between 164 and 122 nm. Li et al. [50] prepared two types of Cu–water nanofluids (25 nm and 100 nm) by two-phase method. The suspension was vibrated for some time of 4 h in an ultrasonicator and observed that the sample was stable in the stationary state. Li et al. [51, 52] mixed Cu nanoparticles (25 nm) in water, with SDBS and CTAB as surfactants, to prepare nanofluid. They found that the nanofluid with CTAB surfactant can be stable for up to one week without any sedimentation, while the suspension without surfactant occurs aggregation immediately. Riehl and Santos [53] mentioned that the Cu–water nanofluids (< 40 nm) were prepared by using an ultrasonicator and observed no sedimentation even after 4 h of observation. Yang et al. [54] prepared Cu (50 nm) nanofluids by using an aqueous solution of cetyl trimethyl ammonium chloride (CTAC) and sodium salicylate (NaSl). The same mass concentration of NaSl and CTAC was added to the solution, whereas water was used as host fluid. An ultrasonicator dispersed the aqueous solution and the nanoparticles in the host fluid. It has also been reported that prepared nanofluid showed a stable property using 3-h of sonication.

Parametthanuwat et al. [55] prepared Ag (< 100 nm) deionized (DI) water nanofluids and sonicated them for 5 h. They found that the nanofluid was stable for 48 h, at $\varphi = 0.5\%$. Hari et al. [56] mentioned that the Ag seed nanoparticles were prepared by chemical reduction of Ag nitrate by sodium borohydride in the presence of tri-sodium citrate to stabilize the particles. Silver nitrate was reduced by ascorbic acid in the presence of seed (mediated chemical synthesis), the micellar template CTAB and sodium hydroxide to prepare nanorods. CTAB was used for capping the silver nanorods. They identified that prepared nanofluids were stabilized for 1 week. Hajian et al. [57] prepared Ag water-based nanofluid by chemical method consisting of reduction of Ag ions, and before the experiment (injection of nanofluids into the heat pipe) started, nanofluids were kept in an ultrasonicator for 15 min to break apart nanoparticles masses and homogenize the nanofluids. Lo et al. [34] prepared Ag (6–25 nm) nanoparticles by SANSS method and observed that nanoparticles were properly mixed in host fluid (DI water) by using an ultrasonicator for 15 min. Moreover, Ag (29 nm) DI water-based nanofluids were prepared using the multi-beam laser ablation method and were stable for several months without adding surfactants [23]. Kang et al. [58] prepared Ag nanoparticles 35 nm in size formed by a catalytic CVD method using an ultrasonicator, where water was considered the base fluid. Asirvatham et al. [59] mixed the Ag nanoparticles (< 100 nm) with DI water without any stabilizer by using an ultrasonicator for 12 h. They mentioned that the nanofluids were uniform, but little accumulation formed.

Kim et al. [60] dispersed Au nanopowder (7.1–12.1 nm) in water with an ultrasonicator for up to 6 h. They suspended the Au nanoparticles in the host fluid by pulsed laser ablation. Despite 6 h of ultrasonication, they reported that the maximum quantity of nanoparticles was precipitated in the host fluid, and the Au nanoparticles stabilized for more than 1 month. Kambli and Mane [61] prepared Au-water nanofluids by reducing an aqueous hydrogen tetrachloroauric acid ($HAuCl_4$) using 1% tri-sodium citrate. The colloidal suspension of different φ was ultrasonicated at room T for 10 min to disperse particles, and optical measurements made using UV–vis Spectrophotometer and suspensions remained stable for 2 weeks. Mondragon et al. [62] synthesized the Au nanoparticles (18.5 nm and 20 nm) with water as host fluid, PBS and citrate buffer solution as a stabilizer by PLAL and photo-fragmentation (PF) technique. The nanofluids prepared by the PLAL-PF technique remain stable over at least 3 months without using any stabilizer. Stakenborg et al. [63] prepared Au nanoparticles of various sizes by adding different quantities of aqueous citrate solution to boiling aqueous Au salt solution. A thiolated DNA probe (1 μM) was mixed with the Au nanoparticles solution (OD ~ 1) in the presence of NaCl, and the suspension was shaken at 800 rpm for ~ 12 h. Paul et al. [64] prepared Au–water nanofluid and informed that uniform distribution, purity of Au nanoparticles and colour of the nanofluids remain stable without any settlement even after 2 days. Patel et al. [65] prepared the Au

and Ag nanoparticles (10–20 nm) by citrate reduction route method. The prepared samples were stable for a few months, and no sedimentation was found during storage during the experiment. Balasubramanian et al. [66] synthesized Au nanofluids such as 5 mg of Au (20 nm) nanoparticles added with 95 mL of $HAuCl_4$ boiled at 100 °C with mechanical stirring for 20 min. Then, 50 mg of trisodium citrate dihydrate (5 mL of 1% solution in water) was added and boiled for 20 min before the sample was gradually cooled to single temperature. Storage in the dark at 4 °C prolongs the stability of purified Au–NP suspensions for up to 20 days. Singh and Soni [67] suspended Al nanoparticle in DI water and polymeric solution ablated for about 20 min. Different types of aqueous stabilizing agent solutions like SDS, PEG, PVA, and PVP are used. For PVA, the particles were stable against oxidation for more than 1 week for all φ. Nanoparticles grown in PVP solution exhibited long-term stability over 3 weeks against oxide formation.

Priya et al. [68] synthesized the CuO nanoparticle in water using an ultrasonicator ~6 h; iron was used as a dispersant for better stability. The CuO:Iron ratio was considered as 2.5:1 and the nanofluid was visually seen to be stable. Suresh et al. [69] followed the same route. Lee et al. [24] prepared CuO–water nanofluid by two-step method with sonication of 6 h and by one-step method with PLAL. They found that the particle size of the nanofluids prepared by the single-step method is less than the two-step method. Yang and Liu [70] mixed CuO nanoparticles into water using an ultrasonicator for 12 h, and the nanofluid was in stable condition for several days. Chang et al. [71] prepared CuO nanoparticles and then synthesized CuO–water nanofluid using a spinning disc reactor (SDR), where NaHMP was used as a dispersant. They found that φ more than 0.40%, the solution was unstable. Kannadasan et al. [72] prepared CuO nanoparticles by using the chemical precipitation method, and CuO nanofluid was produced by mixing the nanoparticle with water surfactant was added to the solution, and a slight settlement was noticed in the suspension even after 25 days of preparation. Fotukian and Esfahany [73] mixed CuO (30–50 nm) and water to prepare nanofluid at different φ. The prepared solution used an ultrasonic mixer for 10 h and showed no sedimentation after 5 h. William et al. [74] prepared CuO water nanofluids using a two-step method, where xanthan gum (XG) was used as a dispersant and an ultrasonic tank was used for sonication of the nanofluid for 1 h. Bhanvase et al. [75] prepared nanofluid by dispersing dry polyaniline (PANI) or PANI–CuO composite nanoparticles into DI water at different φ. The nanofluid was prepared by magnetic stirring and sonication of 30 min, where SLS was the dispersant. Liu et al. [76] mixed the CuO nanoparticles (size of 50 nm, prepared by the gas-condensation method) in the DI–water to prepare the nanofluid and sonicated it for about 10 h using an ultrasonicator. Selvakumar and Suresh [77] prepared CuO nanofluids by mixing the nanoparticles in DI–water with an ultrasonicator for 6 h. They observed stable nanofluids even after a week with little sedimentation. Byrne et al. [78] produced CuO–water nanofluids, with and without surfactant (CTAB), with the help of an ultrasonicator ~7–8 h. They observed that at $\varphi = 0.1\%$, the surfactant-based nanofluid had a particle size of ~200 nm and was stable for 7 days. They mentioned that using a surfactant decreases the nanoparticle size and enhances the dispersion of the nanoparticles. Michael and Iniyan [79] synthesized CuO nanoparticles from Cu acetate by the aqueous precipitation method. Cu acetate monohydrate is a precursor, and glacial AA prevents hydrolysis. This was taken in a flat-bottom beaker and heated with constant stirring. CuO–water nanofluids were prepared with Triton X-100 with and without surfactant (SDBS). After 3 days of preparation, CuO–SDBS water nanofluid showed better stability than Triton X-100.

Anoop et al. [80] used two different types of Al_2O_3 nanoparticles (size of 45 nm and 150 nm), developed by laser evaporated physical method to prepare the Al_2O_3–water nanofluid with the help of ultrasonicator and found that the suspension was stable for several weeks. Esmaeilzadeh et al. [81] prepared Al_2O_3 (15 nm) water nanofluid using magnetic stirring and ultrasonication for 4 h; no sedimentation was found during the experiment. Hegde et al. [82] stirred the Al_2O_3 particle (80 nm in size) with water in a sonicator for 3 h to produce an Al_2O_3–water nanofluid. The prepared nanofluid showed no agglomeration even after the sonication process of 2 h. Mahbubul et al. [83, 84] suspended an Al_2O_3 nanoparticle (13 nm) in water by a two-step method, and the suspension was sonicated for a period of 1–5 h by using a sonic dismembrator machine (20 kHz and 500 W) and nanofluid found to be stable for long days. Ghanbarpour et al. [85] and Das et al. [86] prepared Al_2O_3–water nanofluid by two-step method using surfactants, stirrer and ultrasonicator. Chandrasekar et al. [87] dispersed Al_2O_3 nanoparticles (43 nm) in water using an ultrasonicator for 6 h to prepare nanofluid and noticed that the prepared solution was stable for a few months. Hung et al. [88] produced Al_2O_3 (20 nm)–water nanofluid with φ less than 5% using a homogenizer, an electromagnetic agitator and an ultrasonicator where chitosan was used as a cationic dispersant, and the nanofluid remained stable for 2 weeks. Gharagozloo and Goodson [89] mixed Al_2O_3 (φ of 20%) in water with a maximum of 1% of nitric acid to produce nanofluid. The prepared solution was sonicated for 4 h, and minor settling was observed after a week. Soltani et al. [90] prepared host liquid by adding carboxymethyl cellulose aqueous solutions at $\varphi = 0.5\%$ in water. The dry nanoparticles were dispersed into the host fluid to prepare nanofluid, and before the experiment, the suspension was sonicated for 1 h. Sharma et al. [91] mixed Al_2O_3 nanoparticles (47 nm) in water, whereas SDBS was used as a surfactant, and the suspension was

stirred up to 12 h. They identified that $\varphi < 3\%$, was stable for more than a week, and some sedimentation was identified at maximumφ. Teng et al. [92] prepared Al_2O_3–water nanofluid, chitosan used as a surfactant, with the help of ultrasonicator and electromagnetic agitation. They found that the prepared suspension was stabilized for 1 month. Qu et al. [93] used Al_2O_3 nanoparticles (56 nm) with water by a two-step method, and the dispersion was sonicated for 4 h in an ultrasonicator; and they noticed that the nanofluid could be stable for ~ 72 h. Jung et al. [94] prepared different types of water nanofluids, with and without PVA, using a horn-type ultrasonicator ~ 2 h. They found that suspension was stable for more than 1 month.

Several researchers [95–98] prepared TiO_2 water nanofluids by using a mixer and sonicator and noticed that the prepared nanofluids stable for long periods. Abbasian Arani and Amani [99] diluted TiO_2 nanoparticles in water, and CTAB was used as a surfactant to prepare nanofluids with the support of an ultrasonicator and stirrer to break the accumulation and noticed that the suspension stable for several hours. Mo et al. [100] mixed rutile and anatase nanoparticles (TiO_2) in water (pH adjusted to 8 by using NH_3), and SDS was used as a surfactant. The suspension was mixed using a stirrer for 10 min and sonicated for 40 min and noticed that the nanofluid was stable for 15 days. Bobbo et al. [101] prepared TiO_2 nanofluid using various surfactants (SDS and PEG) and physical treatment methods. They observed that the homogenization method is suitable for improving suspension stability. Nanoparticles are dispersed into water by a high-pressure homogenizer. For TiO_2–water nanofluid, the ratio between nanoparticles and surfactant mass was 1:2 for all φ, and TiO_2–water-PEG solution was less stable. Fedele et al. [102] prepared 35 mass% of TiO_2 nanofluid with bidistilled water. AA is presently used as a dispersant ($\varphi = 1$–5%), and the composition is prepared by 1 h sonication to enhance the sedimentation rate in the nanofluid. Das et al. [37] prepared TiO_2-water-based nanofluid with dispersants like CTAB and AA. The prepared nanofluid mixture was dispersed in the ultrasonic bath for about 2–3 h, and the nanofluid was found stable for several days with negligible disturbance. Duangthongsuk and Wongwises [39] prepared TiO_2-SDBS water nanofluid using an ultrasonicator for 3–4 h and found that the sample was stable up to 3 h of sonication. After that, sedimentation started. Similarly, Murshed et al. [103] mixed TiO_2 nanoparticles in water, where OA and CTAB were used as stabilizers, using 8–10 h ultrasonication. Utomo et al. [104] synthesized TiO_2–water nanofluid (pH constant) by sonicating the suspension for 3 min, where ammonium polyacrylate was used as a surfactant. Kayhani et al. [105] prepared TiO_2 nanoparticles by a chemical process and mixed them in $C_6H_{19}NSi_2$ (hexamethyldisilazane) using a sonicator for 1 h. Then, the nanoparticles were added to water using a sonicator for 3–5 h, marking the nanofluid stable for several days. A similar kind of study was found by He et al. [106], Longo and Zilio [107]. Fedele et al. [108] considered different nanoparticles SWCNHs (100 nm), TiO_2 (21 nm), and CuO (30–50 nm) for preparing the nanofluids by different dispersion techniques; ball milling and high-pressure homogenization, including sonication (0–2 h). They found that the high-pressure homogenization method is the best one. Sen et al. [109] mixed an aqueous alkaline solution (containing mM LiOH and 30 mM KOH) in water for all the nanofluid preparations, and representative salt and additives were used in industrial processes and alkaline. Dry nanopowder was mixed extensively with the host fluid to achieve a homogeneous suspension by magnetic stirring for at least 24 h, and suspensions were resonicated for 4−6 h. Before any testing, nanofluids were sonicated for at least 1 h. Similarly, some other researchers [110–112] prepared TiO_2 and Al_2O_3 nanofluids by mixing the nanoparticles in water, sonicating for 30 min and stirring for 20 min.

Anoop et al. [112] mixed SiO_2 nanoparticles (~ 20 nm) in DI water and deagglomerated the clusters using an ultrasonicator (35 kHz) for 30 min and noticed that the nanofluid was stable for a long time. Bhuiyan et al. [113] applied a two-step method to prepare SiO_2 nanofluids with distilled water. The prepared mixture was vibrated vigorously by a mechanical shaker for 1 h at 150 rpm; subsequently, an ultrasonic homogenizer (frequency of 20 kHz with 50% amplitude) was used for two hours to produce high amplitude to break down particle clusters. Fazeli et al. [114] added SiO_2 nanoparticles with a particle size of 18 nm in water (without surfactant), and the prepared solution was indicated for 90 min. They observed that the nanofluid was stabilized for 3 days without any sedimentation. Bolukbasi and Ciloglu [115] synthesized SiO_2 nanofluid with a two-step procedure at different nanoparticles φ using a stirrer and ultrasonicator for 2 h. They described no sedimentation was found at the time of the experiment. Sulaiman et al. [116] mixed SiO_2 nanoparticles (20 nm) in water and placed them in an ultrasonic bath with different ultrasonication hours (1–5 h). Qu and Wu [117] dispersed two different nanoparticles of SiO_2 (30 nm) and Al_2O_3 (56 nm) in water. The nanofluid was synthesized by a two-step method. No surfactants were added during the synthesis process, and the prepared solution was sonicated for about 4 h. Shahrul et al. [118] mixed SiO_2 nanoparticles (10–20 nm) in water without surfactant and sonicated for 90 min. The sedimentation was observed after 21 days of preparation. Mahian et al. [119] mixed SiO_2 nanoparticles (7 nm) in water, stirrer it for 30 min, and then it was kept in an ultrasonic bath (600 W of power and 40 kHz of frequency). They identified that nanofluids were stable for more than a week. Yang and Liu [120] prepared SiO_2 nanofluid by dispersing silica nanoparticle powders and silane of trimethyoxysilane into the water. In contrast, the mass ratio of reacting silane and nanoparticles was taken as 0.115, and

the prepared nanofluid was stable for 12 months, even at $\varphi = 10\%$ without any sedimentation.

Lee et al. [121] dispersed SiC nanoparticles (< 100 nm) in DI water to prepare nanofluid under various pH and characterized with the zeta potential (ZP) values. SiC–water mixture was sonicated for 12 h for proper dispersion of nanoparticles in the base fluid. Kim et al. [122] prepared SiC–water nanofluid by dispersing the nanoparticles into water and sonicated it for 3 h. From the literature review of SiC nanofluid, it has been confirmed that by adjusting the pH value of nanofluid, SiC nanofluids can be stable for more than 30 days. Ghanbarpour et al. [123] dispersed α-SiC nanoparticles in distilled water to prepare nanofluid at different φ. Then, the suspension was sonicated, and the pH of the nanofluid was adjusted. To study the stability region and identify the optimum pH value of nanofluid, ZP analysis was done in the pH region of 2–10. To know about the real effect of α-SiC nanoparticles on heat pipe performance, surfactant/surface modifiers were avoided. Zhang et al. [124] prepared SiC (30 nm) water-based nanofluids at different φ by using a two-step method, where CTAB was used as the dispersant. The suspension was ultrasonicated for 3–5 h, and the nanofluid remained stable for a week without any sedimentation. Suganthi and Rajan [125] prepared ZnO nanoparticles by chemical precipitation method using zinc nitrate hexahydrate. The nanoparticle was added to sodium hexametaphosphate (surfactant) solution, and the nanoparticle/surfactant ratio was taken as 5:1. Raykar and Singh [126] prepared ZnO nanoparticles by using $(CH_3COO)_2Zn{\cdot}H_2O$, NaOH, water, TEA, stirrer, and, microwave oven. Various types of nanofluids were prepared by dispersing 75 mg (type I), 250 mg (type II) and 500 mg (type III) each in 100 mL of DI water. The solution was indicated for 1 h, and subsequently, 3, 5 and 7 mL of ACAC was added in all types of solutions. All solution was sonicated for 10 min and noticed that nanofluids were stable for up to 12 months. Chung et al. [43] mixed two types of ZnO particles (prepared by sol–gel and physical vapour synthesis) in water; ammonium polymethacrylate was used as a surfactant. They used several sonication systems: a solenoid-actuated bath, a single piezo-actuated bath, and a static bath. They observed that the dispersion by ultrasonic horn was more effective than others. Jeong et al. [127] used two types of ZnO nanopowder for preparing the nanofluids: rectangular-shaped (90–210 nm) and spherical-shaped (20–40 nm). They dispersed ZnO nanopowder in DI water, using ammonium polymethacrylate as a dispersant, and stirred it at 25 °C for different φ nanoparticles from 0.05 to 5.0%. From the above literature study for the ZnO-nanofluid preparation method, long-term stability was observed when ACAC was used as a surfactant, and the minimum sonication was considered for 10 min.

Phuoc et al. [128] produced a nanofluid by adding chitosan in water having 0.5% AA and stirring it for 24 h. Three different mass % (0.1, 0.2, and 0.5) of chitosan and four different mass % (0.5, 1, 2, and 3) of MWCNTS were used for this experiment. Nanofluid was prepared by mixing MWCNTs into the prepared host fluid and sonicated for 10 min, followed by 20 mins of stirring. They found that the solution prepared without chitosan was unstable but stabilized by 0.2% of chitosan-stable for a month. Garg et al. [129] used water, GA and MWCNT to prepare nanofluids. Initially, GA was mixed in water using a stirrer, and the nanoparticle was added to the solution. The prepared samples were sonicated for 5 min by an ultrasonication probe with different sonication times (20 mins to 80 mins). The sonication and stirring process was alternated every 5 minutes and finally noticed that the sample was stable for 1 month. Babu and Prasanna Kumar [130] mixed CNT powder in water to prepare nanofluid. The chemical treatment of CNTs involved soaking of CNTs in an acid mixture for 5 h. The prepared sample was sonicated for 5 min and observed that TCNTs-based nanofluid exhibited better stability than PCNTs-based nanofluid. Ding et al. [131] first sonicated the CNT sample in a bath sonicator for 24 h and dispersed sonicated CNTs into a pre-set amount of water containing GA (surfactant). Finally, the nanofluid was mixed with a high-shear homogenizer for 30 min and found stable for months without visual sedimentation. Sadri et al. [132] used GA, SDBS, and SDS as surfactants in distilled water to prepare CNT nanofluid. The suspension was dispersed using a magnetic stirrer and then sonicated for 20 min using an ultrasonic probe until a homogeneous suspension was achieved. Sarafraz et al. [133] dispersed the desired masses of CNTs (mass% of 0.1–0.3) with a size diameter of 10–20 nm in water by using an ultrasonic process (at 40 kHz, 300 W) for 10 min. Then, nonylphenolethoxylate (alkylphenol organic surfactant) was added dropwise, showing that the nanofluid remained stable for more than 21 days. Su et al. [134] dispersed aligned multiwall carbon nanotubes (A-MWCNTs) in water, and the solution was agitated for 2 h by a sonicator. It was found that the suspension was stable for up to several days without any agglomeration. Abareshi et al. [135] prepared nanofluids which contain different φ Fe_3O_4 nanoparticles by dispersing the nanoparticles in water. Tetramethyl ammonium hydroxide was used as a surfactant and was stable for a few days. Harikrishnan and Kalaiselvam [136] prepared the CuO–OA nanofluid by precipitation method using a sonicator. They found CuO–OA nanofluid dispersion stabilization stable for more days. Hwang et al. [137] prepared several types of nanofluids: MWCNT, CuO and SiO_2 in water and CuO in EG, using an ultrasonic disruptor for 2 h. They obtained a stable suspension for SiO_2 and CuO nanoparticles where

SDS was used as a surfactant to prepare MWCNT nanofluids. Chen et al. [138] produced MWCNTs (15 nm) by CVD method to prepare nanofluids. They chemically treated CNTs into host fluid (distilled water, EG and glycerol), where potassium hydroxide was used as surfactant and observed that all the nanotubes were sedimented after 5 min. From the above literature study, we can conclude that all nanoparticles can mix with water for better stabilization; low φ, appropriate surfactant ratio and optimum sonication time were required.

Water-based hybrid nanofluids

Many researchers used water for preparing the hybrid nanofluids due to better thermal properties. Moldoveanu et al. [139] considered two oxide nanoparticles dispersed in aqueous solution for the analysis: Al_2O_3 nanoparticle (45 nm) in 60% mass water and SiO_2 (20 nm) in 40% mass aqueous solution. Initially, nanofluid was prepared at different φ of 1, 3 and 5% for Al_2O_3 and 1, 2 and 3% for SiO_2–water-based nanofluids. The prepared suspension was sonicated for about 30 min to ensure uniform nanoparticle dispersion. Finally, the appropriate amount of distilled water was mixed into the initial solution and thoroughly mixed and sonicated to achieve the hybrid nanofluids. Suresh et al. [140, 141] produced Al_2O_3-Cu hybrid nanoparticles by hydrogen reduction from a mixture of Al_2O_3 and CuO in a 90:10 mass ratio. The prepared nanofluid was dried to get the precursor powder, and the powder was heated at 900 °C for 1 h to get a mixture of CuO and Al_2O_3. An appropriate amount of Al_2O_3–Cu nanoparticles was mixed in water, where SLS was used as a dispersant, using an ultrasonicator for 6 h to get a stable suspension. The Al_2O_3–Cu water-based hybrid nanofluid was prepared by a two-step method. Balla et al. [142] synthesized CuO–Cu (50 nm) water-based hybrid nanofluids by two-step method for different φ from 0.2 to 1%. Ultrasonic vibration was employed for better mixing of nanoparticles in the host fluid, and no additive was used in the synthesis process.

Nine et al. [143] prepared Al_2O_3–MWNT water-based hybrid nanofluids (mass ratios of 97.5:2.5 up to 90:10). They followed preparation methods like acid treatment and grinding of MWNTs by planetary ball mill to ensure better dispersion. Baghbanzadeh et al. [144] prepared hybrid silica nanosphere/MWCNT followed by wet chemical method. Sodium silicate was mixed with water, and a sonicator dispersed the solution in MWCNTs. Water was also added with CTAB and dimethylformamide by stirrer. Filtering and washing the compounds were done using EG and water until the grey products were demonstrated. Abbasi et al. [145] prepared MWCNT–TiO_2 water nanofluid and TiO_2 nanoparticles produced by hydrolysis of $TiCl_4$. Hybrid nanoparticles of MWCNT–TiO_2 were attained by dropwise adding $TiCl_4$ to water by stirring process and mixing the oxidized MWCNTs in prepared suspension using a sonicator. Munkhbayar et al. [146] prepared Ag/MWCNT hybrid nanofluids for a constant φ of MWCNT and three different φ Ag nanoparticles. The wet grinding method (WGM) was used to mix MWCNTs–water nanofluid and Ag nanoparticles, synthesized by the pulsed wire evaporation (PWE) method. Baghbanzadeha et al. [147] considered distilled water as the host fluid, while MWCNTs, silica nanospheres and two types of their hybrids (ratio of silica and MWCNT are 80:20% and 50:50%) as the suspended particles and SDBS used as the dispersant for preparing nanofluids. First, a desired amount of SDBS was added with distilled water and placed under an ultrasonic disruptor for 2 min. Then, by adding nanomaterials to the prepared solution, the new mixture was sonicated by ultrasonicator for another 20 min. The most stable nanofluid obtained stable for about 1 month without any sedimentation. Jana et al. [148] prepared water-based CNT–Au and CNT–Cu hybrid nanofluid by mixing the water into Au and Cu with the CNT nanoparticle at different φ laurate salt used as a stabilizer for Cu nanoparticle. Megatif et al. [149] prepared Cu-TiO_2hybrid nanoparticles by using the hydrolysis technique. The acid-treated CNTs were mixed with water and sonicated for 30 min. EG and 2-propanol were mixed into the suspension and stirred. Aravind and Ramaprabhu [150] synthesized graphene-MWCNTs through a two-step method. The composite of graphene-wrapped MWCNT was prepared by simple CVD technique and then purified. Madhesh et al. [149] developed a Cu–TiO_2 hybrid nanocomposite by mixing TiO_2 in aqueous solution and adding copper acetate during stirring. As reducing agents, sodium borohydride and ascorbic acid were added to the prepared solution. The prepared solutions remained stable for 2 h to get hybrid nanocomposite, and hybrid nanocomposite powder was again dispersed in host fluid (water) to obtain the hybrid nanofluid. Sundar et al. [151] synthesized the MWCNT-Fe_3O_4 nanocomposite by in situ method. The carboxylated CNT dispersed in water and mixed with ferric and ferrous chloride. Carboxylated-MWCNT was mixed in water by stirrer and washed with acetone to remove the impurities, using sodium hydroxide as a reducing agent. Baby and Ramaprabhu [152] used catalytic CVD to prepare MWNT, and hydrogen-exfoliated graphene (HEG) was synthesized by exfoliating graphite oxide. The hybrid nanostructure (f-MWNT + f-HEG) was dispersed in DI water-based nanofluids, and the solution was sonicated for 1 h and stirred for 24 h. The prepared solution was filtered, dried and used for making nanofluids. Shahsavar et al. [153] synthesized hybrid nanofluids of TMAH with Fe_3O_4 nanoparticles and gum arabic coated on CNT. $FeCl_2$ and $FeCl_3$ were mixed with NH_3, and then, TMAH solution was added until the pure solution was prepared. The excess

NH_3 was evacuated from the solution with the help of a stirrer. Chen et al. [154] mentioned that a green method was applied to prepare a composite of MWNTs decorated with Ag nanoparticles. MWNTs were functionalized using a mechanical ball milling process in the presence of ammonium bicarbonate. The functionalized MWNTs were decorated with Ag–NPs by the traditional silver mirror reaction method. The resulting Ag–MWNT composites were used to prepare a water-based nanofluid. Sundar et al. [155] developed a nanocomposite of MWCNT and Fe_3O_4 by surface modification of MWCNT. Surface modification was involved in mixing MWCNTs in HCl and HNO_3 acid solution by stirring. The in situ and chemical coprecipitation process involved mixing MWCNTs in water and adding $FeCl_2$ to MWCNT.

Esfe et al. [156] prepared a hybrid nanofluid of Cu/TiO_2–water/EG followed by a two-step method at different φ from 0.1 to 2% with the help of a stirrer, and various φ of nanoparticles were mixed with host fluid. Esfe et al. [157] prepared Ag–MgO water-based hybrid nanofluid at different φ followed by one-step and two-step methods. The solution was stabilized using different techniques such as surfactant (CTAB) addition, modifying the pH value, and ultra-sonication and the solution was found to be stable for several days. Madhesh et al. [158] prepared the hybrid nanocomposite of copper-titania. Titania aqueous and copper acetate solutions were stirred with sodium-reducing agent borohydride and ascorbic acid. Syam Sundar et al. [159] used two methods to prepare nanodiamond (ND)-Fe_3O_4 nanofluid. 1.5 g of acid-treated ND was mixed in 50 mL of water and stirred for 2 h. Yarmand et al. [160] synthesized graphene nanoplatelets-Ag nanocomposite and the graphene nanoplatelet was dispersed in a strong acid medium (1:3 ratios) for sonication, about 3 h. Water was used to clean graphene nanoplatelets and dried for a day, and finally, no sedimentation was noticed in the solution for two months. Batmunkh et al. [161] prepared the nanocomposite of Ag and TiO_2 using a ball milling process, and water was used as dispersing media to prepare a hybrid nanofluid. From the above study, we can confirm that most hybrid nanoparticles can mix with water easily, whereas the optimum sonication time, surfactant ratio, and φ nanoparticle are key parameters for better stabilization of hybrid nanofluid.

Ethylene glycol (EG)-based single nanofluids

Robertis et al. [162] prepared EG based nanofluid by single-step technique. Copper nitrate hydrate, sodium hypophosphite monohydrate and polyvinyl pyrrolidone were used as a copper source, reducing agent and stabilizer, respectively. Nanofluid was prepared using the oven (frequency of 2.45 GHz and power of 400 W) and observed that the suspension was settled by about 28.5% in 50 days. They also mentioned that small particles can remain settling for long periods. Sharma et al. [163] mixed Ag particles in EG where silver nitrate was used as a precursor and poly acryl amide-co-acrylic acid (PAA-co-AA) was used as a dispersant. The nanoparticle size and stability were managed by the concentration of PAA-co-AA and the reaction condition. Tamjid and Guenther [164] prepared Ag-diethylene glycol-based nanofluid by VERL technique. The colloid was stirred for 5 minutes in an ultrasonicator to mix the nanoparticle in the host fluid properly. Philip [165] prepared the photoluminescent (PL) nanoparticles of Au with the particle size of 3, 4, 6, and 9 nm by chemical reduction of borohydride/citrate in the presence of PEG and tannic acid. An increase in PL intensity with the addition of KCl was observed for the colloids.

Mostafizur et al. [166] diluted Al_2O_3 with methanol to prepare nanofluid at different φ (particle size = 8 nm) by a two-step method. Ultrasonication homogenizer was used to reduce aggregation. A similar type of preparation was found by Esfe et al. [167]. Abdolbaqi et al. [168] prepared Al_2O_3 nanofluids by dispersing nanoparticles in two mixture ratios, glycol/water (40:60% and 60:40%), in a two-step method. Khdher et al. [169] used Al_2O_3 nanopowder (13 nm) with pure bio glycol as a base fluid to prepare nanofluid by two-step method. Raveshi et al. [170] mixed Al_2O_3 with SDBS, WEG 50 used as host fluid, suspension was sonicated in an ultrasonicator for 2 h and observed that no sedimentation was found even after 3 days. Chen et al. [171] used EG as the base fluid for preparing the TiO_2 (25 nm) nanofluid by a two-step method. They investigated the stabilization and thermal properties with different sonication times (1–40 h). Yapic et al. [172] synthesized the TiO_2 nanoparticle in PEG 200 over particle mass fraction up to 10% using a two-step method. The prepared nanofluid was agitated in an ultrasonicator for 6 h, and the suspension was stable for more than 4 days. Kulkarni et al. [173] prepared several nanofluids, including Al_2O_3 (45 nm), CuO (30 nm) and SiO_2 (50 nm) nanoparticles with water and EG. The nanoparticle was mixed with EG-water solution (60:40), and to avoid accumulation during the experiment, the nanofluid sample was placed in an ultrasonicator bath for 2 h. Abdolbaqi et al. [174] prepared SiO_2 water-based nanofluid, used in the experiment after appropriate dilution, and mixed it with glycol/water (BG/W) with the help of an ultra-sonicator for 2 h. The experiment used different φ of SiO_2 nanofluids with two mixture ratios of BG/W at 20:80% and 30:70%.

Hu et al. [175] dispersed AlN nanoparticles (size of 20 nm) in ethanol where castor oil was used as a surfactant. The prepared solution was stirred in a magnetic stirrer and sonicated in an ultrasonicator for 10 min. They noticed that the nanofluid can be stable for over 2 weeks without agglomeration. A similar study was observed by Yu et al. [176]. Wozniak et al. [177, 178] mixed AlN in PPG 425 and PPG

2000, stirring the prepared solution for 3 h. They observed AlN-PPG 2000 solution was more stable than PPGs 425. Wozniak et al. [179] used AIN nanoparticles (< 100 nm), PPG and PPG 2000 to prepare nanofluid. PPG was used as the dispersive phase for nano-AlN. The liquid is commonly designated as PPG 2000 and AlN–PPG solution prepared by a two-step method. The powder was incrementally added to PPG continuously, and then, the suspension was homogenized. Subsequently, the dispersion was stirred for 40 min at 3000 rpm. It had been assumed that such an intensive stirring broke some AlN agglomerates. Various dispersants and physical treatments were involved in preparing AlN-nanofluids, and at least it can be stable for more than two weeks. Zyla and Fal [180] dispersed AIN (20 nm) nanoparticles in EG to prepare nanofluids. The prepared samples were subjected to mechanical stirring for 30 min, followed by ultrasonication for 200 min. Li et al. [181] prepared an EG-based SiC (30 nm) nanofluid with dispersants like polyvinyl pyrrolidone (PVP) and pH regulator sodium hydroxide (NaOH) by two-step method. SiC nanoparticle suspended in the weighed base fluid at different φ and magnetic stirring used for 1 h to mix the EG/SiC suspension. Simultaneously, a specific amount of PVP and NaOH (pH adjusted to 11) dispersant was added to ensure stable dispersion. An ultrasonication homogenizer was continuously used for 12 h to obtain uniform nanofluid and was found stable after 30 days of preparation.

Moosavi et al. [182] mixed ZnO nanoparticles with different base fluids (EG and glycerol) in a two-step method. They used ammonium citrate as a dispersant and took the mass ratio of particle to dispersant as 1:1. They observed that the prepared suspension was stable for longer periods without any sedimentation and agglomeration. Yu et al. [183]dispersed ZnO nanoparticles (10–20 nm) in EG by stirring and sonicating 3 h for uniform dispersion. Based on the effect of sonication on particle size, it was mentioned that the size of the particle decreased rapidly in the first 3 h; after that, accumulation takes place, and particle size becomes larger. It can be concluded that there is an optimum time of sonication where maximum dispersion can be found. Suganthi et al. [184] prepared ZnO nanopowder using nitrate hexahydrate and ammonium carbonate by chemical precipitation method. Then, the ZnO nanoparticle was mixed in PG/water to prepare the nanofluid. ZnO–water nanofluid was prepared by sequential method in which 4% of ZnO–PG solution was prepared using probe ultrasonication. Water was added to the 4% ZnO–PG dispersion to prepare a 2% ZnO–PG–water nanofluid (PG:water = 50:50%). Other researchers have observed similar types of results [185, 186]. Li et al. [187] prepared EG-based nanofluid containing ZnO nanoparticles (30 nm) with different mass fractions between 1.75 and 10.5% by the two-step method. The nanofluid mixture was mixed with the help of magnetic stirring for 12 h and ultrasonicated for 4 h. Polyvinylpyrrolidone (PVP) was used as a dispersing agent in ZnO-EG nanofluid, and the prepared ZnO-EG nanofluid showed no sedimentation after 48 h. Lee et al. [188] suspended ZnO in EG to prepare nanofluid followed by one-step method (PWE). Saleh et al. [189] prepared ZnO nanoparticles using the chemical precipitation method and mixed those nanoparticles in EG using a magnetic stirrer and sonicator to prepare nanofluids. Kole and Dey [190] dispersed the appropriate amount of ZnO nanoparticles in the measured quantity of EG by ultrasonication (200 W). They observed the optimum time for sonication was 60 h so that the nanofluid could be stable for up to 1 month without any sedimentation. Moattar and Cegincara [191] dried ZnO nanoparticles with the help of an oven to remove moisture. The nanoparticle was mixed in PEG, and the colloid was stirred and agitated thoroughly to make a homogeneous nanofluid by an ultrasonic generator.

Meng et al. [192] dispersed 1 g of CNTs into 60 mL of HNO_3. The particles were added to glycol, followed by a sonication process to obtain CNT glycol nanofluid and they noticed that the nanofluid remained stable for more than two months. Sheikhbahai et al. [193] prepared nanofluids by mixing Fe_3O_4 nanoparticles in EG and followed the sonication process for 1 h. The appropriate amount of water was added to the solution under agitation for 30 min before the experiment, and no sedimentation was found. Syam Sundar et al. [194] mentioned that nanoparticles prepared by the chemical precipitation method can be properly mixed using only an ultrasonication process for 2 h. Several other researchers have prepared EG-based stable nanofluid containing magnetic nanoparticles by different methods [195–197]. Heris [198] prepared CuO (40 nm)–EG/water (60/40)-based nanofluids at different φ of 0.1%, 0.2% and 0.5%. They used an agitator for 6 h to mix the nanoparticle with host fluid, then the solution was kept in a sonicator for 2 h and found that the nanofluid could be stable for up to 1 day. Liu et al. [199] prepared CuO (30 nm)/EG-water-based nanofluid with the help of a super-sonic water bath, surged for ~ 12 h and noticed that the prepared solution was stable for several days. Namburu et al. [200] used CuO nanoparticles (29 nm) with EG and water mixture (60:40). The prepared nanofluid was stirred and agitated for 30 min using an ultrasonicator. Kim et al. [201] synthesized TiO_2 nanoparticles with water and EG, using SDS as a surfactant. The suspension was sonicated in an ultrasonicator for 1 h and stirred for 10 h to get a stabilized nanofluid. Lu et al. [202] dispersed Cu (20 nm) nanoparticles with water and ethanol (host fluid) using an ultrasonic box (25–40 kHz) for 10 h without any surfactant. Mostafizur et al. [203] suspended the spherical SiO_2 nanoparticle (5–15 nm) in methanol at different φ by using a two-step method. First, the suspension was shaken in an incubator. Then, the suspension was stirred

using an ultrasonication homogenizer to overcome strong cohesion between the particles and encourage even distribution of particles. Pang et al. [204] prepared SiO_2 and Al_2O_3 nanofluids by mixing the nanoparticle in methanol, and a sonicator was used for 2 h. The value of ZP of Al_2O_3 nanofluid was more than 60 mV, and for SiO_2 nanofluids, more than 30 mV, indicating good stability for both the nanofluids. From the above literature survey, we can assure that most of the nanoparticles can easily mix with EG,whereas optimum sonication time, particle and surfactant ratio are considered the key parameters for betterstabilization of nanofluid.

Ethylene glycol (EG) based on hybrid nanofluids

Paul et al. [205] followed two-step method to prepare EG-based hybrid nanofluid. Initially, Al–Zn nanoparticles were prepared by mechanical alloying and diluted in EG using sonication and stirring. Toghraie et al. [206] prepared a nanofluid by mixing the same amount of ZnO and TiO_2 nanoparticles into EG using a two-step method. Proper mechanisms like sonication, stirring process and pH value control are employed for a better mixture of nanoparticles in the host fluid. With a stirring of 0.5 h, the nanofluid at different φ was exposed to an ultrasonic processor for 6–7 hrs and no sedimentation was identified for a long time. Sundar et al. [207] prepared hybrid nanodiamond (ND)-nickel (Ni) nanoparticles by in situ method. Initially, ND nanoparticles were mixed in EG, and nickel chloride was added to the solution. Nanosperse was used as a surfactant to secure a homogenous mixture, and the suspension was sonicated for 1 h. ND–Ni-based nanofluids were prepared with 5 different base fluids of EG–water mixtures. Asokan et al. [208] prepared three different types of fluid (water + EG, mono and hybrid nanofluids) for application in compact heat exchangers. $Al_2O_3$and CuO nanoparticles were selected to prepare the hybrid (particle ratio 50:50) and mononanofluids mixed in water–ethylene glycol (60:40)-based mixture fluid. Three different φ (0.02%, 0.04% and 0.06%) of nanofluids were prepared, and the volume of each sample prepared was 8 L. Two-step method was selected to prepare the hybrid nanofluid, and PVP surfactant (ratio of surfactant and particle 1:10) was added in the sample to prevent accumulation. The hybrid nanofluid mixture was stirred for two hours and then kept in an ice bath to prevent the solution from overheating. Finally, an ultrasonicator probe was dipped into the solution.

Aravind and Ramaprabhu [209] prepared a stable nanofluid by mixing the graphene and graphene-MWCNT composite materials in water and EG with a sonication of 30 min. Abbasi et al. [210] prepared γ-Al_2O_3–MWNT hybrid nanofluids using a solvothermal process with ethanol. Aluminium acetate powder was mixed in absolute ethanol under stirring at a normal temperature for 30 min until the aluminium acetate powder dispersed completely. The pristine MWCNTs and the functionalized MWCNTs were added to the solution and synthesized using a sonicator at room temperature until no black agglomerates could be observed in the suspension. Farbod and Ahangarpour [211] prepared hybrid nanofluids using Ag and MWCNTS nanoparticles. Functionalization of MWCNTs executed by mixing the MWCNTs in sulphuric and nitric acid solution. The MWCNTs and pristine decorated with Ag nanoparticles with several φ. $AgNO_3$ was kept in a storage vessel, and ethanol was mixed as a solvent and stirred for 15 min. MWCNTs were added with Ag nanoparticles and ethanol by sonication process and dried to get hybrid nanomaterials. Nearly 42 mg of Ag/MWCNTs nanomaterial was kept in a vessel, and 20 mL of water was mixed to prepare hybrid nanofluids. Afrand et al. [212] obtained a two-step method for preparing SiO_2–MWCNT/SAE 40 and Fe_3O_4–Ag/EG hybrid nanofluids at different φ. The above survey confirmed that most researchers followed the two-step method, sonicator and surfactant, to prepare an EG-based hybrid nanofluid.

Engine oil (EO)-based single nanofluids

Saeedinia et al. [213] mixed CuO nanoparticles with a particle size of 50 nm in oil using an ultrasonicator and noticed that the suspension stable for 24 h and completely sedimented after a week. Colangelo et al. [214] prepared Al_2O_3 (45 nm)-Therminol 66-based nanofluid, used as a surfactant, with an ultrasonic vibrator. Sonawane et al. [215] prepared stable Al_2O_3- aviation turbine fuel (ATF) nanofluid where OA and Tween 20 LR were used as surfactants, and the suspension was sonicated for different hours. They found that the prepared solution was independent of sonication time and stable for more than 24 h. Choi et al. [216] mixed Al_2O_3 (13 nm) and AlN (50 nm) nanoparticles with transformer oil (TO) at φ = up to 4%. Nanoparticles were added with *n*-hexane and surfactant (OA), and the mixture was subjected to bead-milling with ZrO_2 beads. The solution was added with TO and dried off the *n*-hexane using a vacuum evaporator. Xuan and Li [47] prepared Cu–TO and Cu–water-based nanofluids, where the particle size was 100 nm. The TO–Cu suspension stabilized for one week without sedimentation, using 22% of OA. Different percentages of OA were used, and the solution was vibrated for 10 h in an ultrasonicator. Meanwhile, the water–Cu solution stabilized using 9% laurate salts and sonicated in an ultrasonicator. Then, it was noticed that the solution could stable for more than 1 day.

Li et al. [217] followed a two-step method to prepare diathermic oil based SiC nanofluid. SiC nanoparticleswere suspended in the weighted base fluid at different φ and stirred at 500 rpm for 1 h. Then, an ultra-sonication homogenizer was used to sonicate the solution for 6 h to obtain a uniform

nanofluid. They found no sedimentation was observed in the nanofluid after 3 days of preparation. Wei et al. [218] prepared Fe_3O_4 nanoparticles by coprecipitation, mixing the OA to change the nanoparticles. Kerosene was mixed into the mixture after 1 h, and the phase-transfer process occurred spontaneously. After removing the aqueous phase, Fe_3O_4kerosene-based nanofluid was found at $\varphi = 1\%$. Goshayeshi et al. [219] considered OA as surfactant, kerosene as host fluid, as well as α- and γ-Fe_2O_3 nanoparticles prepared from neutrino nanovation to prepare nanofluids. They prepared a 2% nanofluid by dispersing the Fe_2O_3 nanoparticles with host fluid and stirring constantly, and a bath sonicator sonicated the fluid up to 5 h for better stabilization.

Timofeeva et al. [220] added SiO_2 nanopowder (15 nm) in therminol 66 (TH66) as host fluid, where BAC, BZC, and CTAB were used as a surfactant. Surfactant dispersed into the host fluid, and the mixture was stabilized by a magnetic stirrer and sonicator 10 times, 5 min each. The prepared solution can be stable for at least 7 days without any visual phase separation and noticed that BAC was the best surfactant for SiO_2/TH66. Lee et al. [221] used AlN nanoparticles and two dispersing solvents: coolant oil and *n*-Hexane. They prepared nanofluids by adding 0.5% of AlN nanoparticle into coolant oil or *n*-Hexane, then premixed by a homogenizer for 30 min. A surfactant (polyoxyethylene alkyl acid ester, 30 mass% of the particles) was added to the slurry to enhance the dispersion stability. The bead mill operated using different bead sizes and rotation speeds. Katiyar et al. [222] dispersed the required proportion (0–7%) of nanoparticles such as Fe, Ni, and Co in the fluids by utilizing a mechanical stirrer for 60 min at 800–1200 rpm. Subsequently, sonication was carried out for 2–3 h duration at 60% amplitude by utilizing a probe-type ultra-sonicator to break and disperse any accumulation or cluster of nanoparticles. OA was used in minute proportion as a surfactant in the oil-based nanofluids and CTAB for the EG-based magnetic nanofluids to enhance the stability of the suspension and synthesized fluid observed to have a stable of 7–10 days. Agrawal et al.[223] synthesized the CuO nanoparticle using the wet chemical method for two different precursors. Nanofluid from the synthesized nanoparticles was prepared by using a two-step method. Copper acetate, copper sulphate and sodium hydroxide (pellets) were used to synthesize analytic reagent grade, where water, EG, and EO were used as base fluids. Initially, the suspension was stirred for 1 h to increase the stability and remove the accumulation. The nanofluid suspension was sonicated for 30 min using a probe ultrasonic processor (at 220 V), and they observed that the nanofluid was stable for up to 10 days without any sedimentation. Sateesh et al. [224] prepared different nanofluids by dispersing Al_2O_3 nanoparticles in diary scum oil methyl ester for dual fuel engine application with the help of a homogenizer and an ultrasonicator, used to disperse nanoparticles and reduce agglomeration for 1 h. From the above study, it can be concluded that EO-based nanofluid can also be synthesized and stabilized for long periods, mostly with the help of surfactant and sonication.

Engine oil (EO) based on hybrid nanofluids

Han et al. [225] synthesized hybrid sphere/CNT particles by producing the nanoparticle through spray pyrolysis. $Al(NO_3)_3$ and Fe $(NO_3)_3$ nanoparticle composites prepared by thermal decomposition and hybrid sphere/CNT particles were compiled on a membrane filter and dispelled in oil. Kato et al. [226] prepared a polymer hybrid by adding $PbTiO_3$ in silicone oil. $PbTiO_3$ precursor was synthesized from titanium isopropoxide, lead acetate, and 2-(methacryloyloxy) ethyl acetoacetate (MEAA). DI water was used to hydrolyse solid lead acetate and EG monomethyl ether solution. The sonication process was also done for proper dilution of suspension, followed by a stirring process up to 24 h. Botha et al. [227] prepared hybrid nanofluids by one-step method containing silica and silver nanoparticles. Kumar et al. [228] followed the in situ method for preparing Cu–Zn (50:50) hybrid nanofluids. The calculated amount of nanopowder was mixed in vegetable oil and sonicated for 2 h to obtain a stable nanofluid. Esfe et al. [229] used Fe_3O_4–Ag, MWCNTs, SiO_2 nanoparticles and EO (base fluid) to prepare hybrid nanofluids. The measured amount of each component was mixed, stirred and sonicated to obtain a stable condition of the suspension, and the prepared suspensions showed great stability with negligible deposition. Hisham et al. [230] mixed the cellulose nanocrystal and CuO nanoparticle with SAE 40 to prepare hybrid nanofluids followed by a two-step method and noticed that slight sedimentation was found in the 4th week of the preparation. Soltani et al. [231] followed a two-step method to prepare tungsten oxide–MWCNTsEO-based hybrid nanofluids. Once the samples were ready, they were placed on a magnetic stirrer and ultrasonic device for 30 min to have more stability dispersion. Liu et al. [232] dispersed MWCNT–TiO_2 nanoparticles in SAE 20 by a two-step method with the help of a homogenizer. To reduce the nanoparticle clustering in the prepared sample and to improve the stability, an ultrasonic processor was used for 3 h. They observed no sedimentation in any nanofluid sample even after 72 h. Mousavi et al. [233] considered ZnO and molybdenum disulfide (MoS_2) as the precursor, SAE-40 engine oil as the base fluid and Triton X-100 as the surfactant. Initially, the ZnO and MoS_2 particles were added to the oil at different φ. Suspension was mixed using a stirrer for about 3 h and agitated with an ultrasonic agitator for about 45 min. More number of kinds of literature was not available for EO-based hybrid nanofluids.

Based on the previous survey, preparing and stabilizing the EO-based hybrid nanofluid is possible.

Characterization of single and hybrid nanofluids:

A long-term and homogeneous stable nanofluid is a big challenge for scientists and researchers to prepare and apply it for real life because the properties of unstable nanofluids varying with time. Researchers used different techniques and suggested various tests to confirm the homogeneity and stability of the nanofluid. Stability means the nanoparticle is mixed uniformly in the host fluid without agglomeration. Aggregation in the nanoparticle is calculated by the frequency of collisions caused by Brownian motion. The stability of the nanofluid is also related to its electro-kinetic properties, so pH control is required to keep the fluid away from the isoelectric point, which increases stability due to strong repulsive forces. The stability of nanofluid depends on different parameters such as pH, preparation method, characteristics of nanoparticle, sonication time, type of shape and size of the nanoparticles with different base fluids φ and surfactants, etc. The important factor that makes nanofluid unstable is the nanoparticle's aptitude for aggregation due to its high surface charge. The stability of the nanofluid is also calculated by adding van der Waals attractive forces and electrostatic repulsive forces [234]. When electrostatic repulsive forces are more than attractive, stability is achieved. Agglomeration in the nanofluids not only settles and clogs microchannels but also varies thermal properties like thermal conductivity, viscosity, density, etc. So, the aim of the researcher should be to prepare stable nanofluids by using different parameters. The nanoparticle's characterization technique is to identify the nature of the chemical, particle size distribution, morphological behaviour, stabilization, size of the aggregation and many more. This technique is important for verifying particles' interaction or reaction with the base fluid in each nanofluid preparation step. Few techniques have been used in previous studies, such as:

1. Fourier transforms infrared spectroscopy (FTIR): This is required to study the surface chemistry of solid or liquid particles.
2. Scanning electron microscopy (SEM) is done to identify the microstructure and morphological study of nanoparticles or nanostructure materials. Field electron scanning electron microscopy (FESEM) is also a similar technique to SEM.
3. Transmission electron microscopy (TEM) using the wet-TEM technique to analyse the dispersion state is similar to SEM but much higher resolution than SEM.
4. X-ray diffraction (XRD) images are done to identify the particles' crystal structure, and the vibration sample magnetometer (VSM) measures the magnetic properties.
5. Energy-dispersive X-ray spectroscopy (EDX) is required for a sample's elemental analysis or chemical characterization. Thermal gravimetric analysis (TGA) is done to know about the influence of heating and melting on the thermal stability of nanoparticles.
6. UV–Vis spectroscopy is required in analytical chemistry to quantitatively calculate different analytes, such as transition metal ions, highly conjugated organic compounds, and biological macromolecules. Infrared absorption spectroscopy is used to identify chemical substances or functional groups in solid, liquid, or gaseous forms.
7. DLS analysis is conducted to identify the particle size distribution of nanoparticles in the host fluid.
8. Inductively coupled plasma–optical emission spectroscopy (ICP-OES) is used to detect chemical elements. Particle size analyser (PSA) and ZP is tested to identify the stability of the nanofluids.

SEM and TEM are two usual methods to identify the presence of particles in nanofluids. Still, these are not enough to calculate statistical results because only from 10 to 100 particles are identified among many numbers of particles. The particle size was measured using the DLS process to confirm particle size over a larger sample size. The particle undergoes random thermal motion by Brownian movement, while the size of the particle is within 10 µm. The speed of particle movement differs according to the Stokes–Einstein equation depending on the particle size. Lee et al. [235] mentioned that particles small in size move faster than the larger particles. A summary of a few research works on the stability and characterization of single and hybrid nanofluids are mentioned in Tables 4 and 5, respectively.

Application of single and hybrid nanofluids

Nanofluids have improved thermal properties and energy efficiency in various industries and solar systems. Nanofluid can be applied in several areas, such as HT intensification, different kinds of cooling such as electronic, industrial, &nuclear systems, transportation, space and defence, mass

Table 4 Summary of characterization and stability of single nanofluids

Authors name	Material, base fluid and surfactant	Characterization technique used	Duration of stability
Sharma et al. [163]	Ag, EG, Poly acrylamide-co-acrylic acid (PAA-co-AA)	EDX, XRD, TEM, UV–visible spectroscopy, ZP	PSD showed better mixing behaviour in solution with surfactant and stabilized to days
Abareshi et al. [135]	Fe_3O_4, DI–water, Tetramethyl ammonium hydroxide	TEM, XRD, FTIR, VSM, ZP	ZP values showed good dispersion stability
Liu et al. [236]	CNT, EG and EO, *N*-hydroxysuccinimide	HRTEM, SEM, XRD	CNT–EG and CNT–EO suspensions were stable for several hrs
Moosavi et al. [182]	ZnO, ammonium citrate, Glycerol, EG	TEM, SEM, XRD	Nanofluids were stable, at least for a few months
Nikkam et al. [237]	SiC, EG, Water	TEM, DLS, SEM, XRD, FTIR, ZP	Longer stability was found for all prepared nanofluids
Kathiravan et al. [48]	Cu, Water, SDS	AFM, XRD, TEM	Stabilized only during the experimental work
Kole and Dey [49]	Cu, Distilled water	TEM, DLS	The result showed 15 days of stability for the prepared solution
Peng et al. [238]	Cu, Refrigerant (R113),CTAB, SDS, Span-80	TEM	Cu-R113-based nanofluid stable for more than 24 h
Li et al. [51]	Cu, Water, SDBS	TEM, DLS	Better stabilization was found for Cu-H_2O nanofluid than SDBS surfactant suspension
Das et al. [239]	TiO_2, Al_2O_3, TiO_2–anatase, water, CTAB, AA, SDBS, SDS	TEM, DLS, ZP	The settling behaviour of the Al_2O_3 nanofluid was very fast, but TiO_2 nanofluid showed good stability even after 15 days
Balasubramanian et al. [66]	Au, Tetrachloroauric acid, Trisodium citrate dihydrate	TEM, DLS, XPS	The stability of the purified Au nanofluid is up to 20 days
Kannadasan et al. [72]	CuO, Water	XRD	Sedimentation of the nanoparticle was found after 25 days of static condition of nanofluids
Byrne et al. [78]	CuO, Water, CTAB	STEM, DLS	Nanofluid was stable for more than 7 days
Qu et al. [93]	Al_2O_3, Water, HCl	SEM, 2*D* atomic force microscope	Al_2O_3 nanoparticle was added to water and stabilized for 72 h
Shahrul et al. [118]	Al_2O_3, SiO_2, ZnO, Fe_3O_4, SDS, Water, HCTAB, Polyvinylpyrrolidone	Photo-capturing method	No sedimentation was found after a week of preparation
Li et al. [181]	SiC, EG/polyvinyl pyrrolidone, NaOH	TEM, SEM, ZP	Nanofluid was stable for up to 30 days
Agarwal et al. [223]	CuO, Water, EG, EO	UV–Vis, PL, DLS, SEM, TEM and XRD	The stability of the prepared nanofluid was checked for 10 days, and no sedimentation was observed
Kole and Dey [190]	ZnO, EG	TEM, DLS	The stability of ZnO nanofluid was tested for 30 days without any disturbance
Mondragón et al. [62]	Au, Water, PBS, Citrate buffer solution	TEM, EDX, DLS,	Nanofluids have shown good stability
Jung et al. [94]	Al_2O_3, Water, PVA	AFM	The prepared solution was stable for more than 30 days
Longo et al. [107]	Al_2O_3, TiO_2, Water	DLS	Both the nanofluids have shown good stability for more than 1 month
Yang and Liu [120]	Silica, Silane trimethyoxysilane	SEM	The nanoparticle was dispersed well and stable for 1 year at $\varphi = 10\%$
Raykar and Singh [126]	ZnO, Water, ACAC	XRD, FTIR, SEM, DLS, Optical absorption spectra	All the solutions were stable from the date of preparation up to nearly 9 months to 1 year

Table 4 (continued)

Authors name	Material, base fluid and surfactant	Characterization technique used	Duration of stability
Meng et al. [192]	CNT, Glycol	TEM, UV–Vis–NIR transmittance spectra	The prepared nanofluid was stable for more than 60 days without any settlement
Tsai et al. [240]	Au, Water, Trisodium citrate and Tannic acid	TEM, UV–vis spectra	Nanofluid was stable up to 5 days

Table 5 Summary of characterization and stability of hybrid nanofluids

Authors name	Material, Base fluid, Surfactant	Characterization techniques used	Duration of stability
Paul et al. [205]	EG, Al 5% of Zn	SEM, TEM, EDS, XRD	Hybrid nanofluid can remain in stable form for a long period without sedimentation
Nine et al. [143]	Al_2O_3–MWCNT, Water	SEM, TEM, UV–visible spectrophotometry	The hybrid solution showed the same visual effect even after a long period (30 days)
Suresh et al. [140]	Al_2O_3–Cu, Water	XRD, SEM, pH	Hybrid nanofluid was stable for long days due to repulsive forces among the particles
Munkhbayar et al. [146]	Ag, MWCNT, Water	TEM, SEM, UV–visible	The nanofluid is stable up to several days
Baghbanzadeha et al. [147]	MWCNTs, silica nanospheres, Water SDBS	XRD, XPS, TEM	The most stable nanofluid was obtained about 1 month without any sedimentation

transfer enhancement, intensified microreactors, sensing and imaging, energy, mechanical, biomedical and few other applications such as microreactors, brake fluids, microbial fuel cell and unique optical filter properties. Convective HT is one of the most widely studied thermal phenomena in nanofluids, related to several applications. High heat flow processes have conceived important concern for new technologies to increase HT, and microprocessors have become smaller and more energetic, so the heat flux has developed over time, leading to new challenges in thermal systems. In an automotive system, enhanced HT may lead to a smaller heat exchanger for cooling; the result showed that the vehicle's mass was reduced. Managing high thermal loads with conventional coolants possessing inferior HT characteristics is very difficult. Nanofluid plays an important role in several application areas, leading to a major impact in developing future generations of equipment. The application of single and hybrid nanofluids in different areas is mentioned in Tables 6–10. In addition, Figs. 10–13 indicate the experimental setup for the use of single and hybrid nanofluids in various regions.

Challenges of single and hybrid nanofluid

Industries need better thermal management systems for their miniaturized and efficient equipment. Since all the conventional methods have reached their maximum development of new fluids that can transfer heat more efficiently and effectively, it is necessary. Nanofluids have several advantages that can reduce cooling system size, improve reliability, and increase energy and fuel efficiency. It can reduce pumping power compared to a micro-sized particle system. Several challenges and problems of nanofluids are addressed and overcome before their commercial application in the industries. The main issues are as follows:

(a) *Stability of nanoparticle dispersion*: The nanofluid requires long-term stability. Systematic preparation methods for reliable and stable nanofluid have not been established. Preparation of the homogeneous solution is a big challenge since nanoparticles always form aggre-

Table 6 Application of single nanofluid in the area of electronics appliances

Researchers	Materials used	Area of application	Remarks
Tsai et al. [240]	Au	Heat pipe for CPU or desktop	The thermal resistance of the heat pipe with nanofluid was lower than DI water
Kiani et al. [241]	Al_2O_3, AgO, CuO	Lithium-ion battery thermal management system	The cooling efficiency of the system based on nanofluids was improved
Ma et al. [242]	Diamond	Oscillating heat pipe	The heat transport capability of the nanofluid was increased when OHP was charged
Lin et al. [243]	Ag	Pulsating heat pipe	When the heating power is 85 W, the *T* difference and thermal resistance of the evaporator and condenser were decreased by 7.79 °C and 0.092 °C/W, respectively
Kang et al. [244]	Ag	Sintered heat pipe	At the same volume, the nanofluid *T* distribution showed that the *T* difference decreased by 0.56–0.65 °C compared to the DI-water
Nguyen et al. [1]	Al_2O_3	Microprocessors	At $\varphi = 6.8\%$, HTC was enhanced up to 40% compared to base fluid
Roberts et al. [245]	Al_2O_3	Electronics cooling systems	The addition of nanoparticles in the cooling system observed enhancement in convective HT
Naphon et al. [246]	Titanium	Heat pipe	The thermal efficiency of nanofluid was 10.60% higher than base fluid at $\varphi = 0.10\%$
Ho et al. [247]	Al_2O_3	Microchannel heat sink	Friction factor and HTC for nanofluid cooled heat sink were found to be increased
Lee and Mudawar [248]	Al_2O_3	Microchannel heat sink	HTC was higher in the entrance region of the microchannel; enhancement was reduced in the fully developed region
Jung et al. [249]	Al_2O_3	Rectangular microchannel	Convective HTC of Al_2O_3 nanofluid in laminar flow regime was measured to be increased up to 32% compared to base fluid at $\varphi = 1.8\%$
Chein and Chuang [250]	CuO	A microchannel heat sink (MCHS)	Nanofluid-cooled MCHS absorb more energy than water-cooled MCHS when the flow rate is low
Azizi et al. [251]	Cu	Cylindrical microchannel heat sink	The HTC of nanofluid was enhanced compared to base fluid at $\varphi = 0.3\%$
Ho and Chen [252]	Al_2O_3	Minichannel heat sink	The nanofluid-cooled heat sink has higher HTC compared with the water
Tiwari et al. [253]	CeO_2, Al_2O_3, TiO_2, SiO_2	Plate heat exchanger	For CeO_2, Al_2O_3, TiO_2, and SiO_2-based nanofluids, maximum HTC were found ~ 35.9%, 26.3%, 24.1%, and 13.9%, respectively
Bi et al. [254],	TiO_2, Al_2O_3	Domestic refrigerator	When TiO_2 nanoparticles were used, the energy consumption was reduced to 26.1% at $\varphi = 0.1\%$
Peng et al. [255]	CuO	Horizontal smooth tube	HTC of CuO/R113 nanofluid was larger than that of R113 refrigerant. A maximum of 29.7% of HTC was achieved
Bi et al. [256]	TiO_2	Domestic refrigerator	TiO_2-R600a nano-refrigerant saved more energy compared with pure R600a
Naphon et al. [257]	Titanium	Heat pipe	Maximum efficiency was obtained when the nanoparticle was added

gates due to the strong van der Waals interaction. The toxicity of some nanofluids is high.

(b) *Degradation of nanofluids*: The particle in the static nanofluid subjected to Brownian motion may lead to diffusion, limited agglomeration and gravitational settlement. So, it will affect the properties of nanofluid and the feasibility of real applications.

Table 7 Application of single nanofluids in the area of automobile

Researchers	Materials used	Area of application	Remarks
Hussein et al. [258]	TiO_2, SiO_2	Automotive cooling system	SiO_2 nanofluid produced higher HT enhancement than TiO_2 nanofluid and water
Leong et al. [259]	Cu	Automotive car radiator	3.8% of HT enhancement was achieved at $\varphi = 2\%$
Ali et al. [260]	ZnO–water	Car radiator	All φ, nanofluid showed higher HT than the base fluid and HT enhancement up to 46% was found than the base fluid at $\varphi = 0.2\%$
Kulkarni et al. [261]	Al_2O_3	Coolant in a diesel-electric generator	Heat exchanger efficiency increased with φ due to higher HTC of nanofluids
Tzeng et al. [262]	Al_2O_3, CuO	Rotary blade coupling of four-wheel-drive vehicles	They found that CuO has the lowest T distribution at high-low rotating speed and, accordingly best HT effect
Mousavi et al. [263]	CuO–CQD, and Fe_3O_4–CQD	Car radiator coolant	The effectiveness cooling tower was 25% higher at $\varphi = 0.5\%$ for CuO–CQD nanofluid
Oliveira et al. [264]	MWCNTs	Car engine coolant	A slight decrease in the HT rate up to 5% was observed. But as φ of the nanoparticle increased, the HT rate decreased
Bargal et al. [265]	ZnO, AlN	Automotive PEMFC	Adding nanoparticles to the host fluid significantly enhanced the overall HTC and radiator effectiveness, especially at high φ
Subhedar et al. [266]	Al_2O_3	Car radiator coolant	HT performance of the radiator was enhanced by 30% at $\varphi = 0.2\%$ using nanofluid
Akash et al. [267]	Cu, aluminium, MWCNT	Automobile radiator	HTC enhancement was 40%, 29% and 25% for MWCNT, Cu and aluminium nanofluids, respectively
Sateesh et al. [224]	Al_2O_3	Single cylinder four, strokes direct injection diesel engine	Nanofluid results showed an 11.5% amplified brake thermal efficiency, a 23.2% reduction in smoke, and an 18.2–21.4% reduction in hydrocarbon and carbon monoxide emissions

(c) *Cost of nanofluids and Production process:* Another concern for nanofluids is high cost. The size of the nanoparticle causes high manufacturing costs. For production of the nanofluid, it requires a complex and advanced instrument. Due to the difficulties in its production, the cost of nanofluid is high, and there may be a chance of environmental damage when it is drained out after its usage.

(d) *Higher viscosity increased pumping power and pressure drops*: The flow of nanofluid showed a high-pressure drop because of the increase in density and viscosity compared to the conventional fluid, whereas the high pumping power requirement may be the obstacle to enhancing efficiency.

(e) *Lower specific heat and boiling characteristic*: Compared with the host fluid, the specific heat of the nanofluid is low. So, to exchange more heat, researchers have mentioned that the working fluid should have high specific heat. When φ of the nanoparticle increases, the surface T of the nanofluid increases and causes overheating.

(f) *Corrosion and erosion*: The nanoparticle presence in nanofluid may lead to erosion and sometimes corrosion, which may damage the equipment.

(g) *Thermal performance in turbulent flow*: Apart from nanofluid's thermal properties, researchers also focused on the HT performance of nanofluid. Most of the research papers reported that this property was increased with applying nanofluid. The thermal performance of nanofluid in turbulent flow must be addressed.

Table 8 Application of single nanofluids in the area of solar energy

Researchers	Materials used	Area of application	Remarks
Filho et al. [268]	Ag	Direct absorption solar thermal system	Nanofluid has shown good photothermal conversion capability even for low φ
Sani et al. [269]	SWCNH	Solar thermal collector	Results showed that carbon nanohorn-based nanofluids were useful for the enhancement of efficiency
Karami et al. [270]	CNT	Direct absorption solar collector	The presence of 150 ppm-CNT nanofluid increased the extinction coefficient by about 4.1 cm^{-1} than water
Karami et al. [271]	CuO	Direct absorption solar collector	The nanofluid improved the collector efficiency by 9–17% than the base fluid
Meibodi et al. [272],	SiO_2	Flat plate solar collector	SiO_2 nanofluid found an enhancement in efficiency for flat plate solar collectors compared to others
Sardarabadi et al. [273]	SiO_2	Photovoltaic thermal units	The thermal efficiency of the PV/T collector for two different φ of 1 mass% and 3 mass% of the nanofluids was increased by 7.6% and 12.8%, respectively
Li et al. [274]	Al_2O_3, ZnO, MgO	Tubular solar collector	ZnO nanofluid has shown excellent HT performance
Goudarzi et al. [275]	CuO, Al_2O_3	Solar collector with helical tube	They noticed that by using nanofluids, more thermal efficiency can be obtained
Colangelo et al. [276]	Al_2O_3	Flat panel solar thermal collector	Convective HTC of the prepared nanofluid was enhanced up to 25% at $\varphi = 3\%$
Yousefi et al. [277]	Al_2O_3	Flat-plate solar collectors	Nanofluid as a working fluid increased efficiency as compared to water. For $\varphi = 0.2\%$, efficiency increased up to 28.3%
Khullar and Tyagi [278]	Al_2O_3	Solar water heating system	It was identified that if NCSWHS was used as an alternative system, considerable emission reduction and fuel savings could be achieved
Yousefi et al. [279]	MWCNT	Flat-plate solar collector	The result showed that as the φ of the nanofluid increased from 0.2 to 0.4%, the efficiency also increased
Yousefi et al. [280]	MWCNT	Flat-plate solar collector	The effect of nanofluid on the efficiency of the solar collector was increased by increasing or decreasing the pH value
Kasaeian et al. [281]	CNT	Solar parabolic trough collector	The global efficiency of the vacuumed tube was 11% higher than the bare tube efficiency
He et al. [282]	Cu	Flat-plate solar collector	The efficiency of the solar collector was increased up to 23.83% by using nanofluid
Michael and Iniyan [283]	CuO	Photovoltaic thermal collector	Nanofluid has been proven to increase thermal efficiency by up to 45.76%
Lu et al. [284]	CuO	Evacuated tubular solar collector	Nanofluid enhanced the thermal performance of the evaporator, and the HTC also increased up to 30% compared to the base fluid
Liu et al. [285]	Graphene	Direct absorption solar collector	Receiver efficiency was enhanced as φ of the nanoparticle increased
Said et al. [286]	TiO_2	Flat plate solar collector	The energy efficiency was increased by 76.6%, and exergy efficiency was achieved by 16.9% at $\varphi = 0.1\%$ compared to water

(h) *Preparation of hybrid nanofluids*: The major technical challenge is preparing and stabilizing the hybrid nanofluids; it can be obtained with proper dispersion. Mixing two different nanoparticles may pose a surface charge problem, so the selection process for the preparation should consider the following points: an appropriate combination of particles and proper particle bonding. The synthesis method may suppress these in-stabilities to some extent and apply this hybrid nanofluid for solar devices and other HT applications. Hybrid nanofluids are to be prepared to be used for industrial applications. More research needs to be done to understand the complex mechanism behind the augmentation of HT with hybrid nanofluids.

Table 9 Application of single nanofluids in the area of healthcare/biomedical

Researchers	Materials used	Area of application	Remarks
Bakumov et al. [287]	Ag–Si(C) N	Anti-bacterial activity	High anti-bacterial activity found for nanoparticles leads to applications in biomedical, food and other industries
Zhang et al. [288]	ZnO	Antibacterial agent	The result showed that the presence of nanoparticles damages the membrane wall of the bacteria
Zhang et al. [289]	ZnO	Antibacterial agent	Results showed that nanofluid stored for 120 days under light had antibacterial behaviour against *Escherichia coli* DH5a
Jalal et al. [290],	ZnO	Antibacterial activity	The survival ratio of bacteria decreased and produced strong antibacterial activity with increasing φ of ZnO nanofluids and time
Jones et al. [291],	ZnO	Antibacterial activity	ZnO's antibacterial activity depends on the size and presence of normal visible light
Hirota et al. [292],	ZnO	Antibacterial activity	Nanofluid has shown antibacterial activity even under dark conditions
Yamamoto [293]	ZnO	Antibacterial activity	It was found that the antibacterial activity of ZnO increased with decreasing particle size and increasing powder φ
Tam et al. [294]	ZnO	Antibacterial activity	Antibacterial activity in the liquid phase showed cell death occurred due to cell membrane damage
Panacek et al. [295]	Ag	Biomedical	It was observed that the antibacterial activity of the nanoparticle depends on the particle size
Rufus et al. [296]	Hematite (α-Fe_2O_3)	Antibacterial	Bioefficacy and TC enhancement exhibited by nanoparticles may lead to possible applications in environmental and industrial fields
Fakhroueian et al. [297]	ZnO quantum dot nanoparticles	Antibacterial activity, Anticancer	ZnO nanofluid destroyed cancer cell lines more efficiently than the normal HFF-2
Pauzi et al. [298]	ZnO	Antibacterial	ZnO nanofluids have better antibacterial properties compared to unstabilized ZnO nanofluids
Yadav et al. [299]	Au/Pt/Ag	Antibacterial activity	The prepared trimetallic suspension has shown good antibacterial activity and was a better agent than bimetallic and single metallic nanofluid even at low φ
Rufus et al. [300]	hematite (α-Fe_2O_3)	Antibacterial activity	The prepared solution was found to be a potential antibacterial agents
Padil and Černík [301]	CuO	Antibacterial activity	Antibacterial activity experiment found that small particle sizes of nanofluid have higher antibacterial effects and higher zone of inhibition
Nagvenkar et al. [302]	ZnO	Antibacterial activity	The antibacterial activity was enhanced with reduced particle size for the prepared nanofluid

(i) *The selection process of the particles for hybrid nanofluid*: The selection process of hybrid nanoparticles is crucial to obtain the maximum effect. The problems are technical perception, preparation cost and experimentation. More knowledge required about the concept of thermal network and rheological behaviour of hybrid nanofluid. However, many challenges need to be analysed to overcome for various applications.

Table 10 Application of hybrid nanofluids in other areas

Researchers	Materials used	Area of application	Remarks
Li et al. [303]	SiC–MWCNTs	Car radiator system	Convective HTC of SiC–MWCNTs nanofluid was 26% higher than the host fluid
Heidarshenas et al. [304]	Ionic liquid–Al_2O_3	Microchannel heat sink	They mentioned that ionic liquid–alumina hybrid nanofluid can work for small-scale HT devices
Sundar et al. [151]	MWCNT–Fe_3O_4	Constant heat flux circular tube	It was noticed that the Nu enhanced at 31.10% with the increase of pumping power for $\varphi = 0.3\%$ at Re = 22,000 compared to the base fluid
Sundar et al. [305]	(CNT)–Fe_3O_4	Tube with twisted tape	Nu was enhanced up to 42.51% for nanofluid at $\varphi = 0.3\%$ and Re = 22,000, compared to host fluid
Megatif et al. [306]	TiO_2–CNT	Circular tube with constant heat flux	Average HTC was increased up to 33.7% at $\varphi = 0.2$ wt%
Yarmand et al. [160]	GNP–Ag	Circular tube with constant heat flux	Nu was enhanced up to 32.7% with friction factor at $\varphi = 0.1\%$ and Re = 17,500 compared to base fluid
Hameed et al. [307]	Alumina–Cu, Alumina–CNT	Uniformly heated tube	Nu was enhanced up to 30.65% and 20.48% for Alumina–CNT and Alumina–Cu hybrid nanofluids, respectively, compared to base fluid
Sundar et al. [308, 309]	ND–Ni	Tube with longitudinal strip inserts	Nu was enhanced by 35.43% and 93.30% without the insert and with strip insert, respectively, at $\varphi = 0.3\%$ of nanofluid, compared to the base fluid
Hussein et al. [310]	MWCNT–GNP	Mini circular tube	Average HTC was enhanced up to 33.5% at $\varphi = 0.25\%$
Arunachalam et al. [311]	Al_2O_3–Cu	Circular tube with *V*-cut twisted tape	Hybrid nanofluid provided a 42% improvement in Nu
Hamid et al. [312]	TiO_2–SiO_2	Circular tube with constant heat flux	A maximum enhancement of 35.3% in HTC was found for the 40:60 mixture ratio
Hamid et al. [313]	TiO_2–SiO_2	Circular tube with wire coil inserts	A maximum enhancement of 254.4% in Nu was noticed for $\varphi = 2.5\%$
Hussein et al. [314]	MWCNT–GNP	Circular micro-tube	HTC and pressure drop were enhanced by 58.2% and 12.4%, respectively
Dalkilic et al. [315]	Graphite–SiO_2	Circular tube with quad-channel twisted tape insert (QDCC)	HTC increase of 26% was found with QDCC at $\varphi = 1\%$
Suresh et al. [140]	Al_2O_3–Cu	Circular tube	Convective HT was found to have a maximum improvement of 13.56% in Nu compared to base fluid
Kumar and Sarkar [316]	Al_2O_3–MWCNT	Minichannel heat sink	MWCNT water-based nanofluid has shown an enhancement in HTC of 44%
Verma et al. [317]	MgO–MWCNTs, CuO–MWCNTs	Flat plate solar collector	Exergetic and energetic efficiency of the collector for hybrid nanofluid was 71.54% and 70.55% for MgO hybrid nanofluid
Baby and Ramaprabhu [152]	f-MWNT + f-HEG	Heat exchanger	HTC of the prepared suspension increased with an increase in Re. High TC and HTC values of hybrid nanofluids are suggested for coolant application

Table 10 (continued)

Researchers	Materials used	Area of application	Remarks
Hormozi et al. [318]	Al_2O_3–Ag	Coiled heat exchanger	Thermal performance was enhanced up to 16% by using a hybrid nanofluid
Allahyar et al. [319]	Al_2O_3–Ag	Coiled heat exchanger	Nu was increased by 31.6% at Re = 4687 and $\varphi = 0.4\%$
Huang et al. [320]	Al_2O_3–MWCNT	Plate heat exchanger	HTC of hybrid nanofluid was higher than Al_2O_3–water nanofluid
Bhattad et al. [321]	Al_2O_3–MWCNT	Plate heat exchanger	By using a hybrid nanofluid, HTC was increased by 39.16%
Bhattad et al. [322]	Al_2O_3–MWCNT	Counter-flow plate heat exchanger	Maximum enhancement of 15.2% MWCNT (0:5) MoNF produced HTC, and HT of MoNF was better than HyNF
Bhattad et al. [323]	Al_2O_3 + SiC, Al_2O_3 + AlN, Al_2O_3 + MgO, Al_2O_3 + CuO, Al_2O_3 + MWCNT	Plate heat exchanger	A maximum enhancement of 31.2% has been observed in the HTC for Al_2O_3–MWCNT (4:1) hybrid nanofluid
Kumar et al. [324]	Al_2O_3–TiO_2	Minichannel heat sink	A maximum enhancement of 8.5% (numerically) and 12.8% (experimentally) was observed for convective HTC of hybrid nanofluid

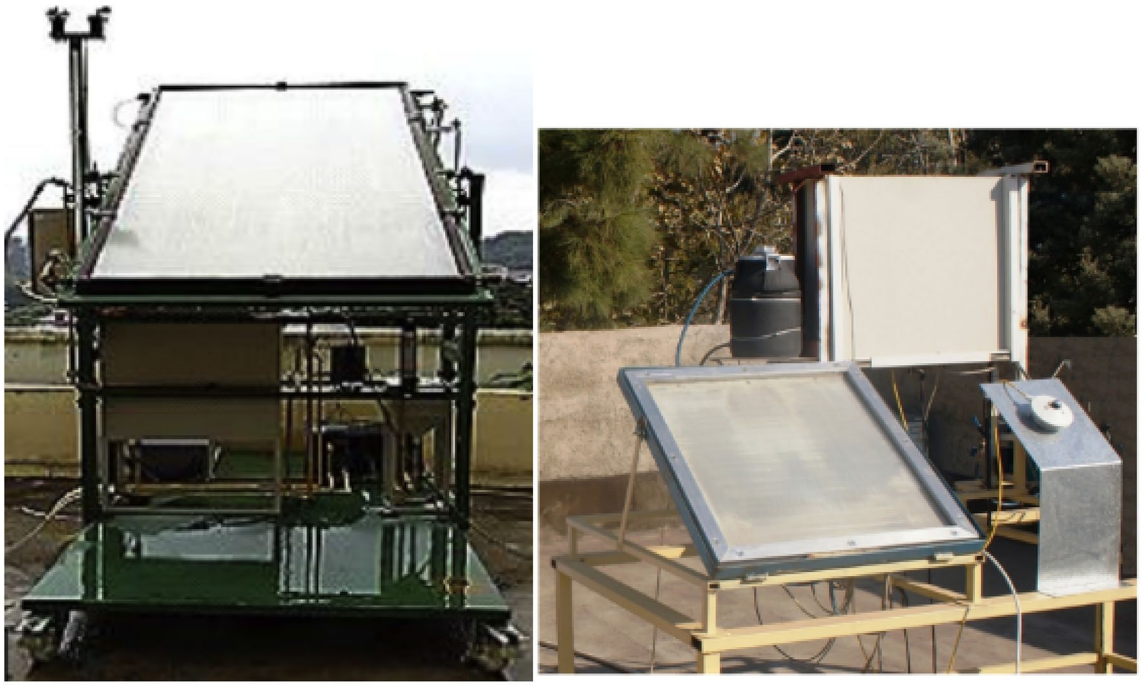

Fig. 10 Shows the experimental setup of **a** flat plate solar collector [286], **b** direct absorption solar collector [271]

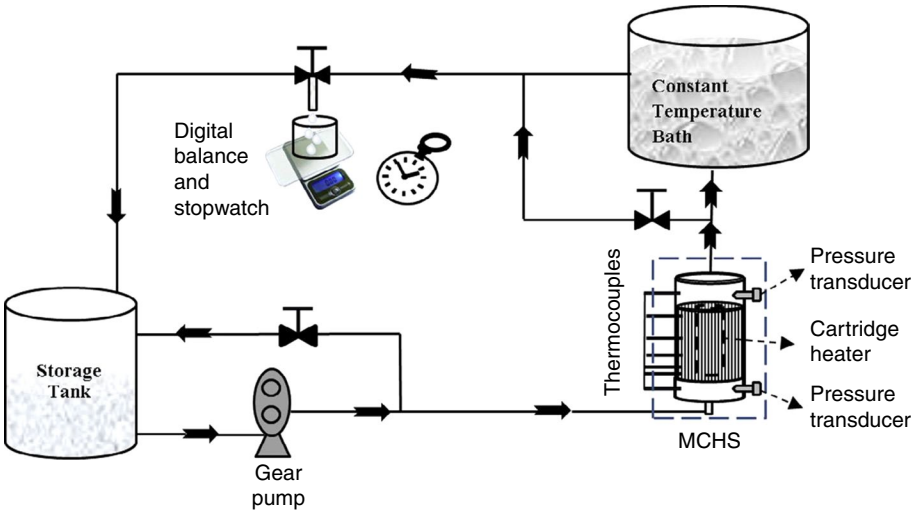

Fig. 11 Shows the experimental setup of cylindrical microchannel heat sink [251]

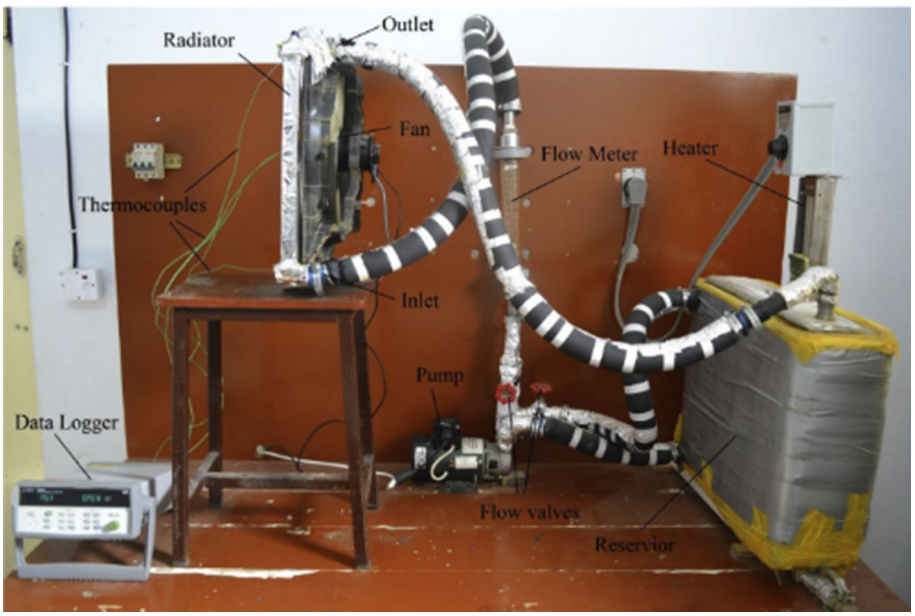

Fig. 12 Shows the experimental setup of car radiator [260]

Future direction of Nanofluids

In the previous section, we have discussed about the application and challenges of normal and hybrid nanofluids. The future research probably focuses on developing efficient energy transfer methods by using hybrid nanofluids. Nanofluid particles can be used to develop microchips that lead to better computers. Additionally, nanofluids can be used as different industrial cooling (microchips and automobile), nanofluids can implement on biomedical (nanocryosurgery, drug delivery, cancer therapeutics, cryopreservation). Hybrid nanoparticles can be used to develop new and improved materials with different properties. Improvement in TC of hybrid nanofluids also helps to make better engines. Nanoparticles can be utilized in various areas, including removing pollutants from water and air, cleaning up contaminated soil, improving the performance of batteries and fuel cells, enhancing sunscreens and personal care products, and serving as food additives to advance preservation and packaging of food items.

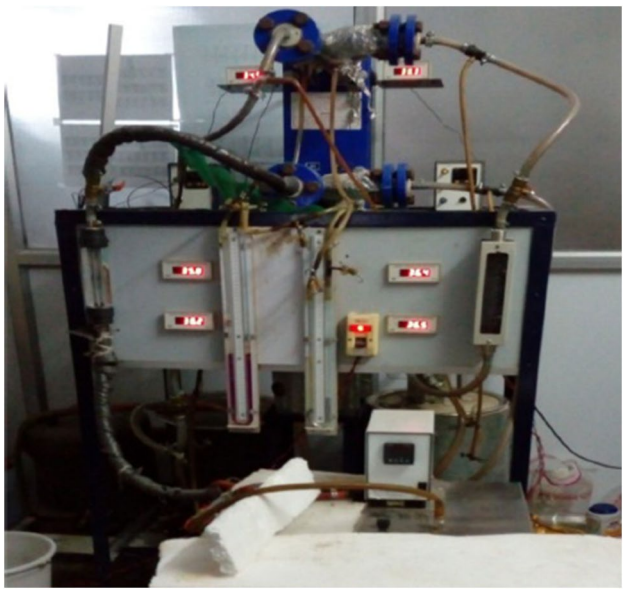

Fig. 13 Shows the experimental setup of plate heat exchanger [323]

Conclusions

Nanofluid is necessary due to its magical properties such as thermal conductivity, viscosity, HT coefficient, and optical properties. Compared with single nanofluid, hybrid nanofluid shows improvement in thermophysical properties. The main aim of this present study is to give detailed knowledge about the preparation of different types of single and hybrid nanofluid with various base fluids, preparation techniques, stabilization processes, characterization, application and challenges.

- The difference between single and hybrid nanofluid is explained in the study's first part. Then, several techniques for the single-step and two-step methods of single and hybrid nanofluid preparation were demonstrated with different base fluids (water, EG, and EO).
- Various surfactants are described that help stabilize the prepared solution, and several characterization methods are suggested for the prepared solution to find stability.
- The author has identified the application of single and hybrid nanofluids in different areas such as electronics, automobiles, solar energy, and healthcare. A few challenges have been identified about nanofluids in this literature, which must be checked carefully before being implemented for industrial application.
- From the above literature study, we have found that all kinds of nanoparticles and hybrid nanoparticles can mix with different base fluids by sonicator and stirrer for better stabilization of the prepared solution; low φ, particle-to-surfactant ratio, optimum sonication time, particle size and chemical composition of nanoparticle are the key parameters. This review article based on single and hybrid nanofluid will help the present and future researchers working in the same field.

Acknowledgements This work was supported by the Qatar National Research Fund under grant no. MME03-1226-210042. The statements made herein are solely the responsibility of the authors.

Author contribution All authors contributed equally to the preparation of the manuscript.

Funding Open Access funding provided by the Qatar National Library. Qatar National Research Fund supported this work under Grant No. MME03-1226-210042. The statements made herein are solely the responsibility of the authors.

Data availability The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no potential conflicts of interest concerning this article's research, authorship, and publication.

Ethical approval This material is the author's original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. The paper reflects the author's research and analysis truthfully and completely.

Consent to participate I have been informed of the risks and benefits involved, and all my questions have been answered satisfactorily. Furthermore, I have been assured that a research team member will also answer any future questions. I voluntarily agree to take part in this study.

Consent to publish Individuals may consent to participate in a study but object to publishing their data in a journal article.

References

1. Nguyen CT, Roy G, Gauthier C, Galanis N. Heat transfer enhancement using Al_2O_3–water nanofluid for an electronic liquid cooling system. Appl Therm Eng. 2007;27:1501–6.

2. Otanicar TP, Phelan PE, Prasher RS, Rosengarten G, Taylor RA. Nanofluid based direct absorption solar collector. J Renew Sustain Energy. 2010;2:033102.
3. Alfellag MA, Kamar HM, Sidik NAC, Muhsan AS, Kazi SN, Alawi OA, Abidin U. Rheological and thermophysical properties of hybrid nanofluids and their application in flat-plate solar collectors: a comprehensive review. J Therm Anal Calorim. 2023;148:6645–86.
4. Shen B, Shih AJ, Tung SC. Application of nanofluids in minimum quantity lubrication grinding. Tribol Trans. 2008;51:730–7.
5. Choi SUS, Eastman JA. Enhancing thermal conductivity of fluids with nanoparticle. ASME Int Mech Eng Congr Expo San Franc. 1995;23:105–99.
6. Gupta J, Pandey BK, Dwivedi DK, Mishra S, Jaiswal R, Pandey S. Experimental studies on thermal conductivity of metal oxides/water–ethylene glycol (50–50%) nanofluids with varying temperature and concentration using ultrasonic interferometer. Phys B. 2023;670:415376.
7. Alfellag MA, Kamar HM, Abidin U, Kazi SN, Azwadi N, Muhsan AS, Alawi OA. Optimizing mixing ratio of multi-walled carbon nanotubes and titanium dioxide: a green approach to high-performance hybrid nanofluids for heat transfer. Powder Technol. 2024;436:119509.
8. Bao Y, Huang A, Zheng X, Qin G. Enhanced photothermal conversion performance of MWCNT/SiC hybrid aqueous nanofluids in direct absorption solar collectors. J Mol Liq. 2023;387:122577.
9. Ajeena AM, Farkas I, Vig P. A comprehensive experimental study on thermal conductivity of ZrO_2–SiC/DW hybrid nanofluid for practical applications: characterization, preparation, stability, and developing a new correlation. Arab J Chem. 2023;1612:105346.
10. Rudyal VY, Pryazhnikov MI, Minakov AV, Shupik AA. Comparison of thermal conductivity of nanofluids with single-walled and multi-walled carbon nanotubes. Diam Relat Mater. 2023;139:110376.
11. Das PK. A review based on the effect and mechanism of thermal conductivity of normal nanofluids and hybrid nanofluids. J Mol Liq. 2017;240:420–46.
12. Yatsuya S, Tsukasaki Y, Mihama K, Uyeda R. Preparation of extremely fine particles by vacuum evaporation onto a running oil substrate. J Cryst Growth. 1978;45:490–4.
13. Choi SUS, Yu W, Hull JR, Zhang ZG, Lockwood FE. Nanofluids for vehicle thermal management. SAE Tech Paper Series. 2001;01:1706.
14. Tran PX, Soong Y. Preparation of nanofluids using laser ablation in liquid technique. ASME applied mechanics and material conference. 2007;915607.
15. Zhu HT, Lin YS, Yin YS. A novel one-step chemical method for preparation of copper nanofluids. J Colloid Interface Sci. 2004;277:100–3.
16. Wang XQ, Mujumdar AS. Heat transfer characteristics of nanofluids: a review. Int J Therm Sci. 2007;46:1–19.
17. Akoh H, Tsukasaki Y, Yatsuya S, Tasaki A. Magnetic properties of ferromagnetic ultra-fine particles prepared by vacuum evaporation on running oil substrate. J Cryst Growth. 1978;45:495–500.
18. Eastman JA, Choi SUS, Li S, Thompson LJ, Lee S. Enhanced thermal conductivity through the development of nanofluids. Mater Res Soc Symp Proc. 1997;457:3–11.
19. Eastman JA, Choi SUS, Li S, Yu W, Thompson LJ. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. Appl Phys Lett. 2001;78:718–20.
20. Ananda Kumar S, Meenakshi KS, Narashimhan BRV, Srikanth S, Arthanareeswaran G. Synthesis and characterization of copper nanofluid by a novel one-step method. Mater Chem Phys. 2009;113:57–62.
21. Kanaras AG, Kamounah FS, Schaumburg K, Kiely CJ, Brust M. Thioalkylated tetra ethylene glycol: a new ligand for water soluble monolayer protected gold clusters. Royal Soc Chem Chem Commun. 2002. https://doi.org/10.1039/b207838b.
22. Liu MS, Lin MCC, Tsai CY, Wang CC. Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method. Int J Heat Mass Transf. 2006;49:3028–33.
23. Phuoc TX, Soong Y, Chyu MK. Synthesis of Ag-deionized water nanofluids using multi-beam laser ablation in liquids. Opt Lasers Eng. 2007;45:1099–106.
24. Lee SW, Park SD, Bang IC. Critical heat flux for CuO nanofluid fabricated by pulsed laser ablation differentiating deposition characteristics. Int J Heat Mass Transf. 2012;55:6908–15.
25. Mafune F, Kohno JY, Takeda Y, Kondow T. Full physical preparation of size-selected gold nanoparticles in solution: laser ablation and laser-induced size control. Am Chem Soc. 2002;106:7575–7.
26. Dolgaev SI, Simakin AV, Voronov VV, Shafeev GA, Verduraz FB. Nanoparticles produced by laser ablation of solids in liquid environment. Appl Surf Sci. 2002;186:546–51.
27. Yang GW. Laser ablation in liquids: applications in the synthesis of nanocrystals. Prog Mater Sci. 2007;52:648–98.
28. Wang H, Xu JZ, Zhu JJ, Chen HY. Preparation of CuO nanoparticles by microwave irradiation. J Cryst Growth. 2002;244:88–94.
29. Singh AK, Raykar VS. Microwave synthesis of silver nanofluids with polyvinylpyrrolidone (PVP) and their transport properties. Colloid Polym Sci. 2008;286:1667–73.
30. Sun Y, Mayers B, Herricks T, Xia Y. Polyol synthesis of uniform silver nanowires: a plausible growth mechanism and the supporting evidence. Nano Lett. 2003;3:955–60.
31. Kim D, Jeong S, Moon J. Synthesis of silver nanoparticles using the polyol process and the influence of precursor injection. Nanotechnology. 2006;17:4019–24.
32. Feldmann C. Polyol-mediated of nanoscale functional materials. Solid State Sci. 2005;7:868–73.
33. Lo CH, Tsunga TT, Chen LC. Shape-controlled synthesis of Cu-based nanofluid using submerged arc nanoparticle synthesis system (SANSS). J Cryst Growth. 2005;277:636–42.
34. Lo CH, Tsung TT, Lin HM. Preparation of silver nanofluid by the submerged arc nanoparticle synthesis system (SANSS). J Alloy Compd. 2007;434–435:659–62.
35. Yang J, Sargent EH, Kelley SO, Ying JY. A general phase-transfer protocol for metal ions and its application in nanocrystal synthesis. Nat Mater. 2009;8:683–9.
36. Kumar A, Joshi HM, Mandale AB, Srivastava R, Adyanthaya SD, Pasricha R, Sastry M. Phase transfer of platinum nanoparticles from aqueous to organic solutions using fatty amine molecules. J Chem Sci. 2004;116:293–300.
37. Das PK, Mallik AK, Santra AK, Ganguly R. Synthesis and characterization of TiO_2–water nanofluids with different surfactants. Int Commun Heat Mass Transf. 2016;75:341–8.
38. Lee S, Choi SUS, Li S, Eastman JA. Measuring thermal conductivity of fluids containing oxide nanoparticles. J Heat Transf. 1999;121:280–9.
39. Duangthongsuk W, Wongwises S. An experimental study on the heat transfer performance and pressure drop of TiO_2–water nanofluids flowing under a turbulent flow regime. Int J Heat Mass Transf. 2010;53:334–44.
40. Fontes DH, Ribatski G, Bandarra EPB. Experimental evaluation of thermal conductivity, viscosity and breakdown voltage AC of

nanofluids of carbon nanotubes and diamond in transformer oil. Diam Relat Mater. 2015;58:115–21.
41. Munkhbayar B, Erdene MB, Ochirkhuyag B, Sarangerel D, Battsengel B, Chung H, Jeong H. An experimental study of the planetary ball milling effect on dispersibility and thermal conductivity of MWCNTs-based aqueous nanofluids. Mater Res Bull. 2012;47:4187–96.
42. Ahammed N, Asirvatham LG, Wongwises S. Thermoelectric cooling of electronic devices with nanofluid in a multiport minichannel heat exchanger. Exp Therm Fluid Sci. 2016;74:81–90.
43. Chung SJ, Leonard JP, Nettleship I, Lee JK, Soong Y, Martello DV, Chyu MK. Characterization of ZnO nanoparticle suspension in water: effectiveness of ultrasonic dispersion. Powder Technol. 2009;194:75–80.
44. Wang XQ, Mujumdar AS. A review on nanofluids part ii: experiments and applications. Braz J Chem Eng. 2008;25:631–48.
45. Manna I. Synthesis, characterization and application of nanofluid–an overview. J Indian Inst Sci. 2009;89:21–33.
46. Prasher R, Phelan PE, Bhattacharya P. Effect of aggregation kinetics on the thermal conductivity of nanoscale colloidal solutions (nanofluid). Nano Lett. 2006;6:1529–34.
47. Xuan Y, Li Q. Heat transfer enhancement of nanofluids. Int J Heat Fluid Flow. 2000;21:58–64.
48. Kathiravan R, Kumar R, Gupta A, Chandra R. Preparation and pool boiling characteristics of copper nanofluids over a flat plate heater. Int J Heat Mass Transf. 2010;53:1673–81.
49. Kole M, Dey TK. Thermal performance of screen mesh wick heat pipes using water-based copper nanofluids. Appl Therm Eng. 2013;50:763–70.
50. Li Q, Xuan Y, Yu F. Experimental investigation of submerged single jet impingement using Cu–water nanofluid. Appl Therm Eng. 2012;36:426–33.
51. Li XF, Zhu DS, Wang XJ, Wang N, Gao JW, Li H. Thermal conductivity enhancement dependent pH and chemical surfactant for Cu–H_2O nanofluids. Thermochim Acta. 2008;469:98–103.
52. Li X, Zhu D, Wang X. Evaluation on dispersion behavior of the aqueous copper nano-suspensions. J Colloid Interface Sci. 2007;310:456–63.
53. Riehl RR, Santos ND. Water–copper nanofluid application in an open loop pulsating heat pipe. Appl Therm Eng. 2012;42:6–10.
54. Yang JC, Li FC, Zhou WW, He YR, Jiang BC. Experimental investigation on the thermal conductivity and shear viscosity of viscoelastic-fluid-based nanofluids. Int J Heat Mass Transf. 2012;55:3160–6.
55. Parametthanuwat T, Rittidech S, Pattiya A. A correlation to predict heat-transfer rates of a two-phase closed thermosyphon (TPCT) using silver nanofluid at normal operating conditions. Int J Heat Mass Transf. 2010;53:4960–5.
56. Hari M, Joseph SA, Mathew S, Nithyaja B, Nampoori VPN, Radhakrishnan P. Thermal diffusivity of nanofluids composed of rod-shaped silver nanoparticles. Int J Therm Sci. 2012;64:188–94.
57. Hajian R, Layeghi M, Sani KA. Experimental study of nanofluid effects on the thermal performance with response time of heat pipe. Energy Convers Manag. 2012;56:63–8.
58. Kang SW, Wei WC, Tsai SH, Yang SY. Experimental investigation of silver nano-fluid on heat pipe thermal performance. Appl Therm Eng. 2006;26:2377–82.
59. Asirvatham LG, Raja B, Lal DM, Wongwises S. Convective heat transfer of nanofluids with correlations. Particuology. 2011;9:626–31.
60. Kim HJ, Bang IC, Onoe J. Characteristic stability of bare Au-water nanofluids fabricated by pulsed laser ablation in liquids. Opt Lasers Eng. 2009;47:532–8.
61. Kambli P, Mane VK. Nanosized Fe_3O_4 an efficient PCR yield enhancer-comparative study with Au, Ag nanoparticles. Colloids Surf B. 2016;141:546–52.
62. Mondragón R, Mendieta RT, Meucci M, Vega GM, Juliá JE, Sani E. Synthesis and characterization of gold/water nanofluids suitable for thermal applications produced by femto second laser radiation. J Photonics Energy. 2016;16:034001.
63. Stakenborg T, Peeters S, Reekmans G, Laureyn W, Jans H, Borghs G, Imberechts H. Increasing the stability of DNA-functionalized gold nanoparticles using mercaptoalkanes. J Nanopart Res. 2008;10:143–52.
64. Paul G, Pal T, Manna I. Thermo-physical property measurement of nano-gold dispersed water based nanofluids prepared by chemical precipitation technique. J Colloid Interface Sci. 2010;349:434–7.
65. Patel HE, Das SK, Sundararajan T, Nair AS, George B, Pradeep T. Thermal conductivities of naked and monolayer protected metal nanoparticle based nanofluids: manifestation of anomalous enhancement and chemical effects. Appl Phys Lett. 2003;83:2931–3.
66. Balasubramanian SK, Yang L, Yung LYL, Ong CN, Ong WY, Yu LE. Characterization, purification, and stability of gold nanoparticles. Biomaterials. 2010;31:9023–30.
67. Singh R, Soni RK. Laser synthesis of aluminium nanoparticles in biocompatible polymer solutions. Appl Phys A. 2014;116:689–701.
68. Priya KR, Suganthi KS, Rajan KS. Transport properties of ultra-low concentration CuO–water nanofluids containing non-spherical nanoparticles. Int J Heat Mass Transf. 2012;55:4734–43.
69. Suresh S, Chandrasekar M, Chandrasekhar S. Experimental studies on heat transfer and friction factor characteristics of CuO/water nanofluid under turbulent flow in a helically dimpled tube. Exp Therm Fluid Sci. 2011;35:542–9.
70. Yang XF, Liu ZH. Flow boiling heat transfer in the evaporator of a loop thermosyphon operating with CuO based aqueous nanofluid. Int J Heat Mass Transf. 2012;55:7375–84.
71. Chang MH, Liu HS, Tai CY. Preparation of copper oxide nanoparticles and its application in nanofluid. Powder Technol. 2011;207:378–86.
72. Kannadasan N, Ramanathan K, Suresh S. Comparison of heat transfer and pressure drop in horizontal and vertical helically coiled heat exchanger with CuO/water based nano fluids. Exp Therm Fluid Sci. 2012;42:64–70.
73. Fotukian SM, Esfahany NM. Experimental study of turbulent convective heat transfer and pressure drop of dilute CuO/water nanofluid inside a circular tube. Int Commun Heat Mass Transf. 2010;37:214–9.
74. William JKM, Ponmani S, Samuel R, Nagarajan R, Sangwai JS. Effect of CuO and ZnO nanofluids in xanthan gum on thermal, electrical and high-pressure rheology of water-based drilling fluids. J Petrol Sci Eng. 2014;117:15–27.
75. Bhanvase BA, Kamath SD, Patil UP, Patil HA, Pandit AB, Sonawane SH. Intensification of heat transfer using PANI nanoparticles and PANI–CuO nanocomposite based nanofluids. Chem Eng Process. 2016;104:172–80.
76. Liu ZH, Li YY, Bao R. Thermal performance of inclined grooved heat pipes using nanofluids. Int J Therm Sci. 2010;49:1680–7.
77. Selvakumar P, Suresh S. Convective performance of CuO/water nanofluid in an electronic heat sink. Exp Therm Fluid Sci. 2012;40:57–63.
78. Byrne MD, Hart RA, Silva AKD. Experimental thermal hydraulic evaluation of CuO nanofluids in microchannels at various concentrations with and without suspension enhancers. Int J Heat Mass Transf. 2012;55:2684–91.
79. Michael JJ, Iniyan S. Performance analysis of a copper sheet laminated photovoltaic thermal collector using copper oxide–water nanofluid. Sol Energy. 2015;119:439–51.

80. Anoop KB, Sundararajan T, Das SK. Effect of particle size on the convective heat transfer in nanofluid in the developing region. Int J Heat Mass Transf. 2009;52:2189–95.
81. Esmaeilzadeh E, Almohammadi H, NasiriVatan S, Omrani AN. Experimental investigation of hydrodynamics and heat transfer characteristics of g-Al_2O_3/water under laminar flow inside a horizontal tube. Int J Therm Sci. 2013;63:31–7.
82. Hegde RN, Rao SS, Reddy RP. Studies on nanoparticle coating due to boiling induced precipitation and its effect on heat transfer enhancement on a vertical cylindrical surface. Exp Therm Fluid Sci. 2012;38:229–36.
83. Mahbubul IM, Shahrul IM, Khaleduzzaman SS, Saidur R, Amalina MA, Turgut A. Experimental investigation on effect of ultrasonication duration on colloidal dispersion and thermophysical properties of alumina–water nanofluid. Int J Heat Mass Transf. 2015;88:73–81.
84. Mahbubul IM, Saidur R, Amalina MA, Niza ME. Influence of ultrasonication duration on rheological properties of nanofluid: an experimental study with alumina–water nanofluid. Int Commun Heat Mass Transf. 2016;76:33–40.
85. Ghanbarpour M, Haghigi EB, Khodabandeh R. Thermal properties and rheological behavior of water based Al_2O_3 nanofluid as a heat transfer fluid. Exp Therm Fluid Sci. 2014;53:227–35.
86. Das PK, Islam N, Santra AK, Ganguly R. Experimental investigation of thermophysical properties of Al_2O_3–water nanofluid: role of surfactants. J Mol Liq. 2017;237:304–12.
87. Chandrasekar M, Suresh S, Chandra BA. Experimental investigations and theoretical determination of thermal conductivity and viscosity of Al_2O_3/water nanofluid. Exp Therm Fluid Sci. 2010;34:210–6.
88. Hung YH, Teng TP, Lin BG. Evaluation of the thermal performance of a heat pipe using alumina nanofluids. Exp Therm Fluid Sci. 2013;44:504–11.
89. Gharagozloo PE, Goodson KE. Temperature-dependent aggregation and diffusion in nanofluids. Int J Heat Mass Transf. 2011;54:797–806.
90. Soltani S, Etemad SG, Thibault J. Pool boiling heat transfer of non-Newtonian nanofluids. Int Commun Heat Mass Transf. 2010;37:29–33.
91. Sharma KV, Syam Sundar L, Sarma PK. Estimation of heat transfer coefficient and friction factor in the transition flow with low volume concentration of Al_2O_3 nanofluid flowing in a circular tube and with twisted tape insert. Int Commun Heat Mass Transf. 2009;36:503–7.
92. Teng TP, Hsu HG, Mo HE, Chen CC. Thermal efficiency of heat pipe with alumina nanofluid. J Alloy Compd. 2010;504:S380–4.
93. Qu J, Wu H, Cheng P. Thermal performance of an oscillating heat pipe with Al_2O_3–water nanofluids. Int Commun Heat Mass Transf. 2010;37:111–5.
94. Jung JY, Kim ES, Kang YT. Stabilizer effect on CHF and boiling heat transfer coefficient of alumina/water nanofluids. Int J Heat Mass Transf. 2012;55:1941–6.
95. Sajadi AR, Kazemi MH. Investigation of turbulent convective heat transfer and pressure drop of TiO_2/water nanofluid in circular tube. Int Commun Heat Mass Transf. 2011;38:1474–8.
96. Mitra S, Saha SK, Chakraborty S, Das S. Study on boiling heat transfer of water–TiO_2 and water MWCNT nanofluids based laminar jet impingement on heated steel surface. Appl Therm Eng. 2012;37:353–9.
97. Suriyawong A, Wongwises S. Nucleate pool boiling heat transfer characteristics of TiO_2–water nanofluids at very low concentrations. Exp Therm Fluid Sci. 2010;34:992–9.
98. Colla L, Fedele L, Buschmann MH. Laminar mixed convection of TiO_2–water nanofluid in horizontal uniformly heated pipe flow. Int J Therm Sci. 2015;97:26–40.
99. Arani AAA, Amani J. Experimental study on the effect of TiO_2–water nanofluid on heat transfer and pressure drop. Exp Therm Fluid Sci. 2012;42:107–15.
100. Mo S, Chen Y, Jia L, Luo X. Investigation on crystallization of TiO_2–water nanofluids and deionized water. Appl Energy. 2012;93:65–70.
101. Bobbo S, Fedele L, Benetti A, Colla L, Fabrizio M, Pagura C, Barison S. Viscosity of water based SWCNH and TiO_2 nanofluids. Exp Therm Fluid Sci. 2012;36:65–71.
102. Fedele L, Colla L, Bobbo S. Viscosity and thermal conductivity measurements of water-based nanofluids containing titanium oxide nanoparticles. Int J Refrig. 2012;35:1359–66.
103. Murshed SMS, Leong KC, Yang C. Enhanced thermal conductivity of TiO_2–water based nanofluids. Int J Therm Sci. 2005;44:367–73.
104. Utomo AT, Poth H, Robbins PT, Pacek AW. Experimental and theoretical studies of thermal conductivity, viscosity and heat transfer coefficient of titania and alumina nanofluids. Int J Heat Mass Transf. 2012;55:7772–81.
105. Kayhani MH, Soltanzadeh H, Heyhat MM, Nazari M, Kowsary F. Experimental study of convective heat transfer and pressure drop of TiO_2/water nanofluid. Int Commun Heat Mass Transf. 2012;39:456–62.
106. He Y, Jin Y, Chen H, Ding Y, Cang D, Lu H. Heat transfer and flow behaviour of aqueous suspensions of TiO_2 nanoparticles (nanofluids) flowing upward through a vertical pipe. Int J Heat Mass Transf. 2007;50:2272–81.
107. Longo GA, Zilio C. Experimental measurement of thermophysical properties of oxide-water nano-fluids down to ice-point. Exp Therm Fluid Sci. 2011;35:1313–24.
108. Fedele L, Colla L, Bobbo S, Barison S, Agresti F. Experimental stability analysis of different water based nanofluids. Nanoscale Res Lett. 2011;6:300.
109. Sen S, Govindarajan V, Pelliccione CJ, Wang J, Miller DJ, Timofeeva EV. Surface modification approach to TiO_2 nanofluids with high particle concentration, low viscosity, and electrochemical activity. ACS Appl Mater Interfaces. 2015;7:20538–47.
110. Duangthongsuk W, Wongwises S. Heat transfer enhancement and pressure drop characteristics of TiO_2–water nanofluid in a double-tube counter flow heat exchanger. Int J Heat Mass Transf. 2009;52:2059–67.
111. Tajik B, Abbassi A, Avval MS, Najafabadi MA. Ultrasonic properties of suspensions of TiO_2 and Al_2O_3 nanoparticles in water. Powder Technol. 2012;217:171–6.
112. Chakraborty S, Saha SK, Pandey JC, Das S. Experimental characterization of concentration of nanofluid by ultrasonic technique. Powder Technol. 2011;210:304–7.
113. Bhuiyan MHU, Saidur R, Mostafizur RM, Mahbubul IM, Amalina MA. Experimental investigation on surface tension of metal oxide water nanofluids. Int Commun Heat Mass Transf. 2015;65:82–8.
114. Fazeli SA, Hashemi SMH, Zirakzadeh H, Ashjaee M. Experimental and numerical investigation of heat transfer in a miniature heat sink utilizing silica nanofluid. Superlattices Microstruct. 2012;51:247–64.
115. Bolukbasi A, Ciloglu D. Pool boiling heat transfer characteristics of vertical cylinder quenched by SiO_2-water nanofluids. Int J Therm Sci. 2011;50:1013–21.
116. Sulaiman MZ, Matsuo D, Enoki K, Okawa T. Systematic measurements of heat transfer characteristics in saturated pool boiling of water-based nanofluids. Int J Heat Mass Transf. 2016;102:264–76.
117. Qu J, Wu H. Thermal performance comparison of oscillating heat pipes with SiO_2/water and Al_2O_3/water nanofluids. Int J Therm Sci. 2011;50:1954–62.

118. Shahrul IM, Mahbubul IM, Saidur R, Sabri MFM. Experimental investigation on Al_2O_3–W, SiO_2–W and ZnO–W nanofluids and their application in a shell and tube heat exchanger. Int J Heat Mass Transf. 2016;97:547–58.
119. Mahian O, Kianifar A, Heris SZ, Wongwises S. Natural convection of silica nanofluids in square and triangular enclosures: Theoretical and experimental study. Int J Heat Mass Transf. 2016;99:792–804.
120. Yang XF, Liu ZH. Pool boiling heat transfer of functionalized nanofluid under sub-atmospheric pressures. Int J Therm Sci. 2011;50:2402–12.
121. Lee SW, Park SD, Kang S, Bang IC, Kim JH. Investigation of viscosity and thermal conductivity of SiC nanofluids for heat transfer applications. Int J Heat Mass Transf. 2011;54:433–8.
122. Kim KM, Jeong YS, Kim IG, Bang IC. Comparison of thermal performances of water-filled, SiC nanofluid-filled and SiC nanoparticles-coated heat pipes. Int J Heat Mass Transf. 2015;88:862–71.
123. Ghanbarpour M, Nikkam N, Khodabandeh R, Toprak MS. Improvement of heat transfer characteristics of cylindrical heat pipe by using SiC nanofluids. Appl Therm Eng. 2015;90:127–35.
124. Zhang J, Diao Y, Zhao Y, Zhang Y. Thermal-hydraulic performance of SiC–water and Al_2O_3–water nanofluids in the minichannel. J Heat Transf. 2016;138(1–9):021705.
125. Suganthi KS, Rajan KS. Temperature induced changes in ZnO–water nanofluid: zeta potential, size distribution and viscosity profiles. Int J Heat Mass Transf. 2012;55:7969–80.
126. Raykar VS, Singh AK. Thermal and rheological behavior of acetylacetone stabilized ZnO nanofluids. Thermochim Acta. 2010;502:60–5.
127. Jeong J, Li C, Kwon Y, Lee J, Kim SH, Yun R. Particle shape effect on the viscosity and thermal conductivity of ZnO nanofluids. Int J Refrig. 2013;36:2233–41.
128. Phuoc TX, Massoudi M, Chen RH. Viscosity and thermal conductivity of nanofluids containing multi-walled carbon nanotubes stabilized by chitosan. Int J Therm Sci. 2011;50:12–8.
129. Garg P, Alvarado JL, Marsh C, Carlson TA, Kessler DA, Annamalai K. An experimental study on the effect of ultrasonication on viscosity and heat transfer performance of multiwall carbon nanotube based aqueous nanofluids. Int J Heat Mass Transf. 2009;52:5090–101.
130. Babu K, Prasanna Kumar TS. Effect of CNT concentration and agitation on surface heat flux during quenching in CNT nanofluids. Int J Heat Mass Transf. 2011;54:106–17.
131. Ding Y, Alias H, Wen D, Williams RA. Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids). Int J Heat Mass Transf. 2006;49:240–50.
132. Sadri R, Ahmadi G, Togun H, Dahari M, Kazi SN, Sadeghinezhad E, Zubir N. An experimental study on thermal conductivity and viscosity of nanofluids containing carbon nanotubes. Nanoscale Res Lett. 2014;9:151.
133. Sarafraz MM, Hormozi F, Nikkhah V. Thermal performance of a counter-current double pipe heat exchanger working with COOH–CNT/water nanofluids. Exp Therm Fluid Sci. 2016;78:41–9.
134. Su F, Ma X, Lan Z. The effect of carbon nanotubes on the physical properties of a binary nanofluid. J Taiwan Inst Chem Eng. 2011;42:252–7.
135. Abareshi M, Goharshadi EK, Zebarjad SM, Fadafan HK, Youssef A. Fabrication, characterization and measurement of thermal conductivity of Fe_3O_4 nanofluids. J Magn Magn Mater. 2010;322:3895–901.
136. Harikrishnan S, Kalaiselvam S. Preparation and thermal characteristics of CuO–oleic acid nanofluids as a phase change material. Thermochim Acta. 2012;533:46–55.
137. Hwang YJ, Ahn YC, Shin HS, Lee CG, Kim GT, Park HS, Lee JK. Investigation on characteristics of thermal conductivity enhancement of nanofluids. Curr Appl Phys. 2006;6:1068–71.
138. Chen L, Xie H, Li Y, Wei Y. Nanofluids containing carbon nanotubes treated by mechanochemical reaction. Thermochim Acta. 2008;477:21–4.
139. Moldoveanu GM, Ibanescu C, Danu M, Minea AA. Viscosity estimation of Al_2O_3, SiO_2 nanofluids and their hybrid: an experimental study. J Mol Liq. 2018;253:188–96.
140. Suresh S, Venkitaraj KP, Selvakumar P, Chandrasekar M. Effect of Al_2O_3–Cu/water hybrid nanofluid in heat transfer. Exp Therm Fluid Sci. 2012;38:54–60.
141. Suresh S, Venkitaraj KP, Selvakumar P, Chandrasekar M. Synthesis of Al_2O_3–Cu/water hybrid nanofluids using two step method and its thermo physical properties. Colloids Surf A Physicochem Eng Asp. 2011;388:41–8.
142. Balla HH, Abdullah S, Faizal WM, Zulkifli R, Sopian K. Numerical study of the enhancement of heat transfer for hybrid CuO–Cu nanofluids flowing in a circular pipe. J Oleo Sci. 2013;62:533–9.
143. Nine MJ, Batmunkh M, Kim JH, Chung HS, Jeong HM. Investigation of Al_2O_3–MWCNTs hybrid dispersion in water and their thermal characterization. J Nanosci Nanotechnol. 2012;12:4553–9.
144. Baghbanzadeh M, Rashidi A, Rashtchian D, Lotfi R, Amrollahi A. Synthesis of spherical silica/multiwall carbon nanotubes hybrid nanostructures and investigation of thermal conductivity of related nanofluids. Thermochim Acta. 2012;549:87–94.
145. Abbasi S, Zebarjad SM, Baghban SHN, Youssefi A, Ekrami-Kakhki MS. Experimental investigation of the rheological behavior and viscosity of decorated multi walled carbon nanotubes with TiO_2 nanoparticles/water nanofluids. J Therm Anal Calorim. 2016;123:81–9.
146. Munkhbayar B, Tanshen MR, Jeoun J, Chung H, Jeong H. Surfactant-free dispersion of silver nanoparticles into MWCNT-aqueous nanofluids prepared by one-step technique and their thermal characteristics. Ceram Int. 2013;39:6415–25.
147. Baghbanzadeha M, Rashidi A, Rashtchian D, Lotfi R, Amrollahi A. Synthesis of spherical silica/multiwall carbon nanotubes hybrid nanostructures and investigation of thermal conductivity of related nanofluids. Thermochim Acta. 2012;549:87–94.
148. Jana S, Khojin AS, Zhong WH. Enhancement of fluid thermal conductivity by the addition of single and hybrid nano-additives. Thermochim Acta. 2007;462:45–55.
149. Madhesh D, Kalaiselvam S. Experimental study on heat transfer and rheological characteristics of hybrid nanofluids for cooling applications. J Exp Nanosci. 2015;10:1194–213.
150. Aravind SSJ, Ramaprabhu S. Graphene wrapped multiwalled carbon nanotubes dispersed nanofluids for heat transfer applications. J Appl Phys. 2012;112:124304.
151. Sundar LS, Singh MK, Sousa AC. Enhanced heat transfer and friction factor of MWCNT–Fe_3O_4/water hybrid nanofluids. Int Commun Heat Mass Transf. 2014;52:73–83.
152. Baby TT, Ramaprabhu S. Experimental investigation of the thermal transport properties of a carbon nanohybrid dispersed nanofluid. Nanoscale. 2011;3:2208–14.
153. Shahsavar A, Salimpour MR, Saghafian M, Shafii MB. An experimental study on the effect of ultrasonication on thermal conductivity of ferrofluid loaded with carbon nanotubes. Thermochim Acta. 2015;617:102–10.
154. Chen L, Yu W, Xie H. Enhanced thermal conductivity of nanofluids containing Ag/MWNT composites. Powder Technol. 2012;231:18–20.
155. Sundar LS, Otero-Irurueta G, Singh MK, Sousa AC. Heat transfer and friction factor of multi-walled carbon nanotubes–Fe_3O_4 nanocomposite nanofluids flow in a tube with/

without longitudinal strip inserts. Int J Heat Mass Transf. 2016;100:691–703.
156. Esfe MH, Wongwises S, Naderi A, Asadi A, Safaei MR, Rostamian H, Dahari M, Karimipour A. Thermal conductivity of Cu/TiO_2–water/EG hybrid nanofluid: experimental data and modeling using artificial neural network and correlation. Int Commun Heat Mass Transf. 2015;66:100–4.
157. Esfe MH, Arani AAA, Rezaie M, Yan WM, Karimipour A. Experimental determination of thermal conductivity and dynamic viscosity of Ag–MgO/water hybrid nanofluid. Int Commun Heat Mass Transf. 2015;66:189–95.
158. Madhesh D, Parameshwaran R, Kalaiselvam S. Experimental investigation on convective heat transfer and rheological characteristics of Cu–TiO_2 hybrid nanofluids. Exp Therm Fluid Sci. 2014;52:104–15.
159. Syam Sundar L, Ramana V, Graça MPF, Singh MK, Sousa ACM. Nanodiamond–Fe_3O_4 nanofluids: preparation and measurement of viscosity, electrical and thermal conductivities. Int Commun Heat Mass Transf. 2016;73:62–74.
160. Yarmand H, Gharehkhani S, Ahmadi G, Shirazi SFS, Baradaran S, Montazer E, Zubir MNM, Alehashem MS, Kazi SN, Dahari M. Graphene nanoplatelets–silver hybrid nanofluids for enhanced heat transfer. Energy Convers Manag. 2015;100:419–28.
161. Batmunkh M, Tanshen MR, Nine MJ, Myekhlai M, Choi H, Chung H, Jeong H. Thermal conductivity of TiO_2 nanoparticles based aqueous nanofluids with an addition of a modified silver particle. Ind Eng Chem Res. 2014;53:8445–51.
162. Robertis ED, Cosme EHH, Neves RS, Kuznetsov AY, Campos APC, Landi SM, Achete CA. Application of the modulated temperature differential scanning calorimetry technique for the determination of the specific heat of copper nanofluids. Appl Therm Eng. 2012;41:10–7.
163. Sharma P, Baek I, Cho T, Park S, Lee KB. Enhancement of thermal conductivity of ethylene glycol-based silver nanofluids. Powder Technol. 2011;208:7–19.
164. Tamjid E, Guenther BH. Rheology and colloidal structure of silver nanoparticles dispersed in diethylene glycol. Powder Technol. 2010;197:49–53.
165. Philip D. Synthesis and spectroscopic characterization of gold nanoparticles. Spectrochimica Acta Part A. 2008;71:80–5.
166. Mostafizur RM, Saidur R, Aziz ARA, Bhuiyan MHU. Thermophysical properties of methanol based Al_2O_3 nanofluids. Int J Heat Mass Transf. 2015;85:414–9.
167. Esfe MH, Karimipour A, Yan WM, Akbari M, Safaei MR, Dahari M. Experimental study on thermal conductivity of ethylene glycol based nanofluids containing Al_2O_3 nanoparticles. Int J Heat Mass Transf. 2015;88:728–34.
168. Abdolbaqi MK, Azmi WH, Mamat R, Sharma KV, Najafi G. Experimental investigation of thermal conductivity and electrical conductivity of BioGlycol–water mixture based Al_2O_3 nanofluid. Appl Therm Eng. 2016;102:932–41.
169. Khdher AM, Sidik NAC, Hamzah WAW, Mamat R. An experimental determination of thermal conductivity and electrical conductivity of bio glycol based Al_2O_3 nanofluids and development of new correlation. Int Commun Heat Mass Transf. 2016;73:75–83.
170. Raveshi MR, Keshavarz A, Mojarrad MS, Amiri S. Experimental investigation of pool boiling heat transfer enhancement of alumina/water-ethylene glycol nanofluids. Exp Therm Fluid Sci. 2013;44:805–14.
171. Chen H, Ding Y, Tan C. Rheological behaviour of nanofluids. New J Phys. 2007;9:367.
172. Yapicil K, Cakmak NK, Ilhan N, Uludag Y. Rheological characterization of polyethylene glycol based TiO_2 nanofluids. Korea–Aust Rheol J. 2014;26:355–63.
173. Kulkarni DP, Das DK, Vajjha RS. Application of nanofluids in heating buildings and reducing pollution. Appl Energy. 2009;86:2566–73.
174. Abdolbaqi MK, Sidik NAC, Rahim MFA, Mamat R, Azmi WH, Yazid MNAWM, Najafi G. Experimental investigation and development of new correlation for thermal conductivity and viscosity of BioGlycol/water based SiO_2 nanofluids. Int Commun Heat Mass Transf. 2016;77:54–63.
175. Hu P, Shan WL, Yu F, Chen ZS. Thermal conductivity of AlN-ethanol nanofluids. Int J Thermophys. 2008;29:1968–73.
176. Yu W, Xie H, Li Y, Chen L. Experimental investigation on thermal conductivity and viscosity of aluminum nitride nanofluid. Particuology. 2011;9:187–91.
177. Wozniak M, Rutkowski P, Kata D, Szafran M. New anhydrous aluminum nitride dispersions as potential heat-transferring media. Powder Technol. 2013;235:717–22.
178. Wozniak M, Danelska A, Rutkowski P, Kata D. Thermal conductivity of highly loaded aluminium nitride–poly (propylene glycol) dispersions. Int J Heat Mass Transf. 2013;65:592–8.
179. Wozniak M, Rutkowski P, Kata D. Rheological properties and thermal conductivity of AlN–poly (propylene glycol) suspensions. Heat Mass Transf. 2016;52:103–12.
180. Zyła G, Fal J. Experimental studies on viscosity, thermal and electrical conductivity of aluminum nitride-ethylene glycol (AlN–EG) nanofluids. Thermochim Acta. 2016;637:11–6.
181. Li X, Zou C, Lei X, Li W. Stability and enhanced thermal conductivity of ethylene glycol-based SiC nanofluids. Int J Heat Mass Transf. 2015;89:613–9.
182. Moosavi M, Goharshadi EK, Yousefi A. Fabrication, characterization, and measurement of some physicochemical properties of ZnO nanofluids. Int J Heat Fluid Flow. 2010;31:599–605.
183. Yu W, Xie H, Chen L, Li Y. Investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluid. Thermochim Acta. 2009;491:92–6.
184. Suganthi KS, Vinodhan VL, Rajan KS. ZnO–propylene glycol-water nanofluids with improved properties for potential applications in renewable energy and thermal management. Colloids Surf A Physicochem Eng Asp. 2016;506:63–73.
185. Suganthi KS, Vinodhan VL, Rajan KS. Heat transfer performance and transport properties of ZnO–ethylene glycol and ZnO–ethylene glycol–water nanofluid coolants. Appl Energy. 2014;135:548–59.
186. Suganthi KS, Rajan KS. A formulation strategy for preparation of ZnO–Propylene glycol-water nanofluids with improved transport properties. Int J Heat Mass Transf. 2014;71:653–63.
187. Li H, Wang L, He Y, Hu Y, Zhu J, Jiang B. Experimental investigation of thermal conductivity and viscosity of ethylene glycol based ZnO nanofluids. Appl Therm Eng. 2015;88:363–8.
188. Lee GJ, Kima CK, Lee MK, Rhee CK, Kim S, Kim C. Thermal conductivity enhancement of ZnO nanofluid using a one-step physical method. Thermochim Acta. 2012;542:24–7.
189. Saleh R, Putra N, Prakoso SP, Septiadi WN. Experimental investigation of thermal conductivity and heat pipe thermal performance of ZnO nanofluids. Int J Therm Sci. 2013;63:125–32.
190. Kole M, Dey TK. Thermophysical and pool boiling characteristics of ZnO–ethylene glycol nanofluids. Int J Therm Sci. 2012;62:61–70.
191. Moattar MTZ, Cegincara RM. Effect of temperature on volumetric and transport properties of nanofluids containing ZnO nanoparticles poly (ethylene glycol) and water. J Chem Thermodyn. 2012;54:55–67.
192. Meng Z, Daxiong W, Wang L, Zhu H, Li Q. Carbon nanotube glycol nanofluids: photo-thermal properties, thermal conductivities and rheological behavior. Particuology. 2012;10:614–8.

193. Sheikhbahai M, Esfahany MN, Etesami N. Experimental investigation of pool boiling of Fe_3O_4/ethylene glycol–water nanofluid in electric field. Int J Therm Sci. 2012;62:149–53.
194. Syam Sundar L, Ramana EV, Singh MK, De Sousa ACM. Viscosity of low volume concentrations of magnetic Fe_3O_4 nanoparticles dispersed in ethylene glycol and water mixture. Chem Phys Lett. 2012;554:236–42.
195. Abareshi M, Sajjadi SH, Zebarjad SM, Goharshadi EK. Fabrication, characterization, and measurement of viscosity of α-Fe_2O_3–glycerol nanofluids. J Mol Liq. 2011;163:27–32.
196. Pastoriza-Gallego MJ, Lugo L, Legido JL, Pineiro MM. Enhancement of thermal conductivity and volumetric behavior of Fe_xO_y nanofluids. J Appl Phys. 2011;110:014309.
197. Asadzadeh F, Esfahany MN, Etesami N. Natural convective heat transfer of Fe_3O_4/ethylene glycol nanofluid in electric field. Int J Therm Sci. 2012;62:114–9.
198. Heris SZ. Experimental investigation of pool boiling characteristics of low-concentrated CuO/ethylene glycol-water nanofluids. Int Commun Heat Mass Transf. 2011;38:1470–3.
199. Liu ZH, Xiong JG, Bao R. Boiling heat transfer characteristics of nanofluids in a flat heat pipe evaporator with micro-grooved heating surface. Int J Multiph Flow. 2007;33:1284–95.
200. Namburu PK, Kulkarni DP, Misra D, Das DK. Viscosity of copper oxide nanoparticles dispersed in ethylene glycol and water mixture. Exp Therm Fluid Sci. 2007;32:397–402.
201. Kim SH, Choi SR, Kim D. Thermal conductivity of metal-oxide nanofluids: particle size dependence and effect of laser irradiation. J Heat Transf. 2007;129:298–307.
202. LuL LvLC, LiuZH A. of Cu–water and Cu–ethanol nanofluids in a small flat capillary pumped loop. Thermochim Acta. 2011;512:98–104.
203. Mostafizur RM, Aziz ARA, Saidur R, Bhuiyan MHU. Investigation on stability and viscosity of SiO_2–CH_3OH (methanol) nanofluids. Int Commun Heat Mass Transf. 2016;72:16–22.
204. Pang C, Jung JY, Lee JW, Kang YT. Thermal conductivity measurement of methanol-based nanofluids with Al_2O_3 and SiO_2 nanoparticles. Int J Heat Mass Transf. 2012;55:5597–602.
205. Paul G, Philip J, Raj B, Das PK, Manna I. Synthesis, characterization, and thermal property measurement of nano-$Al_{95}Zn_{05}$ dispersed nanofluid prepared by a two-step process. Int J Heat Mass Transf. 2011;54:3783–8.
206. Toghraie D, Chaharsoghi VA, Afrand M. Measurement of thermal conductivity of ZnO–TiO_2/EG hybrid nanofluid effects of temperature and nanoparticles concentration. J Therm Anal Calorim. 2016;125:527–35.
207. Sundar LS, Singh MK, Ramana EV, Singh B, Grácio J, Sousa AC. Enhanced thermal conductivity and viscosity of nanodiamond-nickel nanocomposite nanofluids. Sci Rep. 2014;4:4039.
208. Asokan N, Gunnasegaran P, Wanatasanappan VV. Experimental investigation on the thermal performance of compact heat exchanger and the rheological properties of low concentration mono and hybrid nanofluids containing Al_2O_3 and CuO nanoparticles. Therm Sci Eng Prog. 2020;20:100727.
209. Aravind SSJ, Ramaprabhu S. Graphene–multiwalled carbon nanotube-based nanofluids for improved heat dissipation. RSC Adv. 2013;13:4199–206.
210. Abbasi SM, Rashidi A, Nemati A, Arzani K. The effect of functionalisation method on the stability and the thermal conductivity of nanofluid hybrids of carbon nanotubes/gamma alumina. Ceram Int. 2013;39:3885–91.
211. Farbod M, Ahangarpour A. Improved thermal conductivity of Ag decorated carbon nanotubes water based nanofluids. Phys Lett A. 2016;380:4044–8.
212. Afrand M, Toghraie D, Ruhani B. Effects of temperature and nanoparticles concentration on rheological behavior of Fe_3O_4–Ag/EG hybrid nanofluid: an experimental study. Exp Therm Fluid Sci. 2016;77:38–44.
213. Saeedinia M, Behabadi MAA, Nasr M. Experimental study on heat transfer and pressure drop of nanofluid flow in a horizontal coiled wire inserted tube under constant heat flux. Exp Therm Fluid Sci. 2012;36:158–68.
214. Colangelo G, Favale E, Miglietta P, Milanese M, Risi A. Thermal conductivity, viscosity and stability of Al_2O_3-diathermic oil nanofluids for solar energy systems. Energy. 2016;95:124–36.
215. Sonawane S, Patankar K, Fogla A, Puranik B, Bhandarkar U, Sunil KS. An experimental investigation of thermo-physical properties and heat transfer performance of Al_2O_3-aviation turbine fuel nanofluids. Appl Therm Eng. 2011;31:2841–9.
216. Choi C, Yoo HS, Oh JM. Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants. Curr Appl Phys. 2008;8:710–2.
217. Li X, Zou C, Zhou L, Qi A. Experimental study on the thermophysical properties of diathermic oil based SiC nanofluids for high temperature applications. Int J Heat Mass Transf. 2016;97:631–7.
218. Wei Y, Xie H, Chen L, Li Y. Enhancement of thermal conductivity of kerosene-based Fe_3O_4 nanofluids prepared via phase-transfer method. Colloids Surf A. 2010;355:109–13.
219. Goshayeshi HR, Safaei MR, Goodarzi M, Dahari M. Particle size and type effects on heat transfer enhancement of ferro-nanofluids in a pulsating heat pipe. Powder Technol. 2016;301:1218–26.
220. Timofeeva EV, Moravek MR, Singh D. Improving the heat transfer efficiency of synthetic oil with silica nanoparticles. J Colloid Interface Sci. 2011;364:71–9.
221. Lee SH, Jung MH, Choi C, Moon H, Chung CB. Modeling of a bead mill process for dispersion of coagulated nano particles. Powder Technol. 2013;233:96–102.
222. Katiyar A, Dhar P, Nandi T, Das SK. Enhanced heat conduction characteristics of Fe, Ni and Co nanofluids influenced by magnetic field. Exp Therm Fluid Sci. 2016;78:345–53.
223. Agarwal R, Verma K, Agrawal NK, Duchaniya RK, Singh R. Synthesis, characterization, thermal conductivity and sensitivity of CuO Nanofluids. Appl Therm Eng. 2016;102:1024–36.
224. Sateesh KA, Yaliwal VS, Elahi M, Soudagar M, Banapurmath NR, Fayaz H, Safaei MR, Elfasakhany A, EL Seesy AI. Utilization of biodiesel/Al_2O_3 nanoparticles for combustion behavior enhancement of a diesel engine operated on dual fuel mode. J Therm Anal Calorim. 2021;147:1–15.
225. Han ZH, Yang B, Kim SH, Zachariah MR. Application of hybrid sphere/carbon nanotube particles in nanofluids. Nanotechnology. 2007;18:105701.
226. Kato Y, Mimura KI, Umeda J, Sakamoto W, Yogo T. Synthesis of field responsive $PbTiO_3$ particle/polymer hybrids from metal-organics. Colloids Surf A. 2012;408:57–63.
227. Botha SS, Ndungu P, Bladergroen BJ. Physicochemical properties of oil-based nanofluids containing hybrid structures of silver nanoparticles supported on silica. Ind Eng Chem Res. 2011;50:3071–7.
228. Kumar MS, Vasu V, Gopal AV. Thermal conductivity and rheological studies for Cu–Zn hybrid nanofluids with various base fluids. J Taiwan Inst Chem Eng. 2016;66:321–7.
229. Esfe MH, Afrand M, Yan WM, Yarmand H, Toghraie D, Dahari M. Effects of temperature and concentration on rheological behavior of MWCNTs/SiO_2 (20–80)-SAE40 hybrid nano-lubricant. Int Commun Heat Mass Transf. 2016;76:133–8.
230. Hisham S, Kadirgama K, Mohammed HA, Kumar A, Ramasamy D, Samykano M, Rahman S. Hybrid nanocellulose-copper (II) oxide as engine oil additives for tribological behavior improvement. Molecules. 2020;25(2975):1–16.

231. Soltani F, Toghraie D, Karimipour A. Experimental measurements of thermal conductivity of engine oil-based hybrid and mono nanofluids with tungsten oxide (WO_3) and MWCNTs inclusions. Powder Technol. 2020;371:37–44.
232. Liu K, Zhang Y, Dai F, Sun W. Improved heat transfer of the engine oil by changing it to hybrid nanofluid: adding hybrid nano-powders. Powder Technol. 2021;383:56–64.
233. Mousavia SB, Herisa SZ, Estell'e P. Viscosity, tribological and physicochemical features of ZnO and MoS_2 diesel oil-based nanofluids: an experimental study. Fuel. 2021;293:120481.
234. Das PK, Mallik AK, Ganguly R, Santra AK. Stability and thermophysical measurements of TiO_2 (anatase) nanofluids with different surfactants. J Mol Liq. 2018;254:98–107.
235. Lee J, Han K, Koo J. A novel method to evaluate dispersion stability of nanofluids. Int J Heat Mass Transf. 2014;70:421–9.
236. Liu MS, Lin MCC, Huang IT, Wang CC. Enhancement of thermal conductivity with carbon nano-tube for nanofluids. Int Commun Heat Mass Transf. 2005;32:1202–10.
237. Nikkam N, Saleemi M, Haghighi EB, Ghanbarpour M, Khodabandeh R, Muhammed M, Palm B, Toprak MS. Fabrication, characterization and thermo-physical property evaluation of water ethylene glycol based SiC nanofluids for heat transfer applications. Nano Micro Lett. 2014;6:178–89.
238. Peng H, Ding G, Haitao H. Effect of surfactant additives on nucleate pool boiling heat transfer of refrigerant-based nanofluid. Exp Therm Fluid Sci. 2011;35:960–70.
239. Das PK, Mallik AK, Hossain Mola A, Santra AK, Ganguly R, Saha A, Kumar S, Aswal VK. Experimental investigation for stability and surface properties of TiO_2 and Al_2O_3 water based nanofluids. J Therm Anal Calorim. 2021;10894:1–19.
240. Tsai CY, Chien HT, Ding PP, Chan B, Luh TY, Chen PH. Effect of structural character of gold nanoparticles in nanofluid on heat pipe thermal performance. Mater Lett. 2004;58:1461–5.
241. Kiani M, Omiddezyani S, Houshfar E, Miremadi SR, Ashjaee M, Nejad AM. Lithium-ion battery thermal management system with Al_2O_3/AgO/CuO nanofluids and phase change material. Appl Therm Eng. 2020;180:115840.
242. Ma HB, Wilson C, Borgmeyer B, Park K, Yu Q, Choi SUS, Tirumala M. Effect of nanofluid on the heat transport capability in an oscillating heat pipe. Appl Phys Lett. 2006;88(1–3):143116.
243. Lin YH, Kang SW, Chen HL. Effect of silver nano-fluid on pulsating heat pipe thermal performance. Appl Therm Eng. 2008;28:1312–7.
244. Kang SW, Wei WC, Tsai SH, Huang CC. Experimental investigation of nanofluids on sintered heat pipe thermal performance. Appl Therm Eng. 2009;29:973–9.
245. Roberts NA, Walker DG. Convective performance of nanofluids in commercial electronics cooling systems. Appl Therm Eng. 2010;30:2499–504.
246. Naphon P, Assadamongkol P, Borirak T. Experimental investigation of titanium nanofluids on the heat pipe thermal efficiency. Int Commun Heat Mass Transf. 2008;35:1316–9.
247. Ho CJ, Wei LC, Li ZW. An experimental investigation of forced convective cooling performance of a microchannel heat sink with Al_2O_3–water nanofluid. Appl Therm Eng. 2010;30:96–103.
248. Lee J, Mudawar I. Assessment of the effectiveness of nanofluids for single-phase and two-phase heat transfer in micro-channels. Int J Heat Mass Transf. 2007;50:452–63.
249. Jung JY, Oh HS, Kwak HY. Forced convective heat transfer of nanofluids in micro channels. Int J Heat Mass Transf. 2009;52:466–72.
250. Chein R, Chuang J. Experimental microchannel heat sink performance studies using nanofluids. Int J Therm Sci. 2007;46:57–66.
251. Azizi Z, Alamdari A, Malayeri MR. Convective heat transfer of Cu–water nanofluid in a cylindrical microchannel heat sink. Energy Convers Manag. 2015;101:515–24.
252. Ho CJ, Chen WC. An experimental study on thermal performance of Al_2O_3–water nanofluid in a minichannel heat sink. Appl Therm Eng. 2013;50:516–22.
253. Tiwari AK, Ghosh P, Sarkar J. Performance comparison of the plate heat exchanger using different nanofluids. Exp Therm Fluid Sci. 2013;49:141–51.
254. Bi S, Shi L, Zhang L. Application of nanoparticles in domestic refrigerators. Appl Therm Eng. 2008;28:1834–43.
255. Peng H, Ding G, Jiang W, Hu H, Gao Y. Heat transfer characteristics of refrigerant based nanofluid flow boiling inside a horizontal smooth tube. Int J Refrig. 2009;32:1259–70.
256. Bi S, Guo K, Liu Z, Wu J. Performance of a domestic refrigerator using TiO_2-R600a nano-refrigerant as working fluid. Energy Convers Manag. 2011;52:733–7.
257. Naphon P, Thongkum D, Assadamongkol P. Heat pipe efficiency enhancement with refrigerant nanoparticles mixtures. Energy Convers Manag. 2009;50:772–6.
258. Hussein AM, Bakar RA, Kadirgama K, Sharma KV. Heat transfer enhancement using nanofluids in an automotive cooling system. Int Commun Heat Mass Transf. 2014;53:195–202.
259. Leong KY, Saidur R, Kazi SN, Mamun AH. Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator). Appl Therm Eng. 2010;30:2685–92.
260. Ali HM, Ali H, Liaquat H, Maqsood HTB, Nadir MA. Experimental investigation of convective heat transfer augmentation for car radiator using ZnO–water nanofluids. Energy. 2015;84:317–24.
261. Kulkarni DP, Vajjha RS, Das DK, Oliva D. Application of Al_2O_3 nanofluids in diesel electric generator as jacket water coolant. Appl Therm Eng. 2008;28:1774–81.
262. Tzeng SC, Lin CW, Huang KD. Heat transfer enhancement of nanofluids in rotary blade coupling of four-wheel-drive vehicles. Acta Mech. 2005;179:11–23.
263. Mousavi H, Mostafa S, Ghomshe T, Rashidi A, Mirzaei M. Hybrids carbon quantum dots as new nanofluids for heat transfer enhancement in wet cooling towers. Heat Mass Transf. 2021;58:03077.
264. Oliveira GA, Cardenas Contreras EM, Bandarra Filho EP. Experimental study on the heat transfer of MWCNT/water nanofluid flowing in a car radiator. Appl Therm Eng. 2017;111:1450–6.
265. Bargal MHS, Souby MM, Abdelkareem MAA, Sayed M, Qi T, Chen M, Wang Y. Experimental investigation of the thermal performance of a radiator using various nanofluids for automotive PEMFC applications. Int J Energy Res. 2021;45:6831–49.
266. Subhedara DG, Ramani BM, Gupta A. Experimental investigation of heat transfer potential of Al_2O_3/Water–Mono Ethylene Glycol nanofluids as a car radiator coolant. Case Stud Therm Eng. 2018;11:26–34.
267. Akasha AR, Abrahama S, Pattamattaa A, Das SK. Experimental assessment of the thermo-hydraulic performance of automobile radiator with metallic and non-metallic nanofluids. Heat Transf Eng. 2020;41:1521–37.
268. Filho EPB, Mendoza OSH, Beicker CLL, Menezes A, Wen D. Experimental investigation of a silver nanoparticle-based direct absorption solar thermal system. Energy Convers Manag. 2014;84:261–7.
269. Sani E, Mercatelli L, Barison S, Pagura C, Agresti F, Colla L, Sansoni P. Potential of carbon nanohorn-based suspensions for solar thermal collectors. Sol Energy Mater Sol Cells. 2011;95:2994–3000.
270. Karami M, Bahabadi MAA, Delfani S, Ghozatloo A. A new application of carbon nanotubes nanofluid as working fluid of low-temperature direct absorption solar collector. Sol Energy Mater Sol Cells. 2014;121:114–8.

271. Karami M, Bahabadi MAA, Delfani S, Raisee M. Experimental investigation of CuO nanofluid-based direct absorption solar collector for residential applications. Renew Sustain Energy Rev. 2015;52:793–801.
272. Meibodi SS, Kianifar A, Niazmand H, Mahian O, Wongwises S. Experimental investigation on the thermal efficiency and performance characteristics of a flat plate solar collector using SiO_2/EG–water nanofluids. Int Commun Heat Mass Transf. 2015;65:71–5.
273. Sardarabadi M, Fard MP, Heris ZS. Experimental investigation of the effects of silica/water nanofluid on PV/T (photovoltaic thermal units). Energy. 2014;66:264–72.
274. Li Y, Xie H, Yu W, Li J. Investigation on heat transfer performances of nanofluids in solar collector. Mater Sci Forum. 2011;694:33–6.
275. Goudarzi K, Nejati F, Shojaeizadeh E, Yousuf SKA. Experimental study on the effect of pH variation of nanofluids on the thermal efficiency of a solar collector with helical tube. Exp Thermal Fluid Sci. 2015;60:20–7.
276. Colangelo G, Favale E, Risi AD, Laforgia D. A new solution for reduced sedimentation flat panel solar thermal collector using nanofluids. Appl Energy. 2013;111:80–93.
277. Yousefi T, Veysi F, Shojaeizadeh E, Zinadini S. An experimental investigation on the effect of Al_2O_3–H_2O nanofluid on the efficiency of flat-plate solar collectors. Renewable Energy. 2012;39:293–8.
278. Khullar V, Tyagi H. A study on environmental impact of nanofluid-based concentrating solar water heating system. Int J Environ Stud. 2012;69:220–32.
279. Yousefi T, Veisy F, Shojaeizadeh E, Zinadini S. An experimental investigation on the effect of MWCNT–H_2O nanofluid on the efficiency of flat-plate solar collectors. Exp Therm Fluid Sci. 2012;39:207–12.
280. Yousefi T, Shojaeizadeh E, Veysi F, Zinadini S. An experimental investigation on the effect of pH variation of MWCNT–H_2O nanofluid on the efficiency of a flat-plate solar collector. Sol Energy. 2012;86:771–9.
281. Kasaeian A, Daviran S, Azarian RD, Rashidi A. Performance evaluation and nanofluid using capability study of a solar parabolic trough collector. Energy Convers Manag. 2015;89:368–75.
282. He Q, Zeng S, Wang S. Experimental investigation on the efficiency of flat plate solar collectors with nanofluids. Appl Therm Eng. 2015;88:165–71.
283. Michael JJ, Iniyan S. Performance of copper oxide/water nanofluid in a flat plate solar water heater under natural and forced circulations. Energy Convers Manag. 2015;95:160–9.
284. Lu L, Liu ZH, Xiao HS. Thermal performance of an open thermosyphon using nanofluids for high-temperature evacuated tubular solar collectors part 1: indoor experiment. Sol Energy. 2011;85:379–87.
285. Liu J, Ye Z, Zhang L, Fang X, Zhang Z. A combined numerical and experimental study on graphene/ionic liquid nanofluid based direct absorption solar collector. Solar Energy Mater Solar Cells. 2015;136:177–86.
286. Said Z, Sabiha MA, Saidur R, Hepbasli A, Rahim NA, Mekhilef S, Ward TA. Performance enhancement of a flat plate solar collector using TiO_2 nanofluid and polyethylene glycol dispersant. J Clean Prod. 2015;92:343–53.
287. Bakumov V, Gueinzius K, Hermann C, Schwarz M, Kroke E. Polysilazane-derived antibacterial silver–ceramic nanocomposites. J Eur Ceram Soc. 2007;27:3287–92.
288. Zhang L, Jiang Y, Ding Y, Povey M, York D. Investigation into the antibacterial behaviour of suspensions of ZnO nanoparticles (ZnO nanofluids). J Nanopart Res. 2007;9:479–89.
289. Zhang L, Ding Y, Povey M, York D. ZnO nanofluids-a potential antibacterial agent. Prog Nat Sci. 2008;18:939–44.
290. Jalal R, Goharshadi EK, Abareshi M, Moosavi M, Yousefi A, Nancarrow P. ZnO nanofluids: green synthesis, characterization, and antibacterial activity. Mater Chem Phys. 2010;121:198–201.
291. Jones N, Ray B, Ranjit KT, Manna AC. Antibacterial activity of ZnO nanoparticle suspensions on a broad spectrum of microorganisms. FEMS Microbiol Lett. 2008;279:71–6.
292. Hirota K, Sugimoto M, Kato M, Tsukagoshi K, Tanigawa T, Sugimoto H. Preparation of zinc oxide ceramics with a sustainable antibacterial activity under dark conditions. Ceram Int. 2010;36:497–506.
293. Yamamoto O. Influence of particle size on the antibacterial activity of zinc oxide. Int J Inorg Mater. 2001;3:643–6.
294. Tam KH, Djurišić AB, Chan CMN, Xi YY, Tse CW, Leung YH, Chan WK, Leung FCC, Au DWT. Antibacterial activity of ZnO nanorods prepared by a hydrothermal method. Thin Solid Films. 2008;516:6167–74.
295. Panacek A, Kvitek L, Prucek R, Kolar M, Vecerova R, Pizurova N, Sharma VK, Neveena T, Zboril R. Silver colloid nanoparticles: synthesis, characterization, and their antibacterial activity. J Phys Chem B. 2006;110:16248–53.
296. Rufus A, Sreeju N, Philip D. Synthesis of biogenic hematite (α-Fe_2O_3) nanoparticles for antibacterial and nanofluid applications. RSC Adv. 2016;6:94206–17.
297. Fakhroueian Z, Vahabpour R, Assmar M, Massiha A, Zahedi A, Esmaeilzadeh P, Katouzian F, Rezaei S, Keyhanvar P, Dehshiri AM. ZnO Q-dots as a potent therapeutic nanomedicine for in vitro cytotoxicity evaluation of mouth KB44, breast MCF7, colon HT29 and HeLa cancer cell lines, mouse ear swelling tests in vivo and its side effects using the animal model. Artif cells, nanomed biotechnol. 2018;46:96–111.
298. Pauzi N, Zain NM, Yusuf NAA. Gum arabic as natural stabilizing agent in green synthesis of ZnO nanofluids for antibacterial application. J Environ Chem Eng. 2020;8:103331.
299. Yadav N, Jaiswal AK, Dey KK, Yadav VB, Nath G, Srivastava AK, Yadav RR. Trimetallic Au/Pt/Ag based nanofluid for enhanced antibacterial response. Mater Chem Phys. 2018;218:10–7.
300. Rufus A, Sreeju N, Vilas V, Philip D. Biosynthesis of hematite (α-Fe_2O_3) nanostructures: size effects on applications in thermal conductivity, catalysis, and antibacterial activity. J Mol Liq. 2017;242:537–49.
301. Padil VVT, Černík M. Green synthesis of copper oxide nanoparticles using gum karaya as a biotemplate and their antibacterial application. Int J Nanomed. 2013;8:889–98.
302. Nagvenkar AP, Deokar A, Perelshteina I, Gedanken A. A one-step sonochemical synthesis of stable ZnO–PVA nanocolloid as a potential biocidal agent. J Mater Chem B. 2016;4:2124–32.
303. Lia X, Wanga H, Luo B. The thermophysical properties and enhanced heat transfer performance of SiC–MWCNTs hybrid nanofluids for car radiator system. Colloids Surf A. 2021;12:125968.
304. Heidarshenas A, Azizi Z, Peyghambarzadeh SM, Sayyahi S. Experimental investigation of heat transfer enhancement using ionic liquid–Al_2O_3 hybrid nanofluid in a cylindrical microchannel heat sink. Appl Therm Eng. 2021;191:116879.
305. Syam Sundar L, Sousa A, Singh MK. Heat transfer enhancement of low volume concentration of carbon nanotube-Fe_3O_4/water hybrid nanofluids in a tube with twisted tape inserts under turbulent flow. J Therm Sci Eng Appl. 2015;7:021015.
306. Megatif L, Ghozatloo A, Arimi A, Shariati-Niasar M. Investigation of laminar convective heat transfer of a novel TiO_2–carbon nanotube hybrid water-based nanofluid. Exp Heat Transf. 2016;29:124–38.
307. Hameed MS, Suresh S, Singh RK. Comparative study of heat transfer and friction characteristics of water-based

alumina–copper and Alumina–CNT hybrid nanofluids in laminar flow through pipes. J Therm Anal Calorim. 2019;136:243–53.
308. Sundar LS, Singh MK, Sousa AC. Turbulent heat transfer and friction factor of nanodiamond–nickel hybrid nanofluids flow in a tube: an experimental study. Int J Heat Mass Transf. 2018;117:223–34.
309. Sundar LS, Singh MK, Sousa AC. Heat transfer and friction factor of nanodiamond-nickel hybrid nanofluids flow in a tube with longitudinal strip inserts. Int J Heat Mass Transf. 2018;121:390–401.
310. Hussien AA, Abdullah MZ, Yusop NM, Moh'd A, Atieh MA, Mehrali M. Experiment on forced convective heat transfer enhancement using MWCNTs/GNPs hybrid nanofluid and mini-tube. Int J Heat Mass Transf. 2017;115:1121–31.
311. Arunachalam U, Edwin M. Experimental studies on laminar flow heat transfer in nanofluids flowing through a straight circular tube with and without V-cut twisted tape insert. Heat Mass Transf. 2018;54:673–83.
312. Hamid KA, Azmi W, Nabil M, Mamat R. Experimental investigation of nanoparticle mixture ratios on TiO_2–SiO_2 nanofluids heat transfer performance under turbulent flow. Int J Heat Mass Transf. 2018;118:617–27.
313. Hamid KA, Azmi W, Mamat R, Sharma K. Heat transfer performance of TiO_2–SiO_2 nanofluids in a tube with wire coil inserts. Appl Therm Eng. 2019;152:275–86.
314. Hussien AA, Abdullah MZ, Yusop NM, Al-Kouz W, Mahmoudi E, Mehrali M. Heat transfer and entropy generation abilities of MWCNTs/GNPs hybrid nanofluids in microtubes. Entropy. 2019;21:480.
315. Dalkılıç AS, Türk OA, Mercan H, Nakkaew S, Wongwises S. An experimental investigation on heat transfer characteristics of graphite-SiO_2/water hybrid nanofluid flow in horizontal tube with various quad-channel twisted tape inserts. Int Commun Heat Mass Transf. 2019;107:1–13.
316. Kumar V, Sarkar J. Particle ratio optimization of Al_2O_3–MWCNT hybrid nanofluid in minichannel heat sink for best hydrothermal performance. Appl Therm Eng. 2020;165:114546.
317. Verma SK, Tiwari AK, Tiwari S, Chauhan DS. Performance analysis of hybrid nanofluids in flat plate solar collector as an advanced working fluid. Sol Energy. 2018;167:231–41.
318. Hormozi F, ZareNezhad B, Allahyar H. An experimental investigation on the effects of surfactants on the thermal performance of hybrid nanofluids in helical coil heat exchangers. Int Commun Heat Mass Transf. 2016;78:271–6.
319. Allahyar H, Hormozi F, ZareNezhad B. Experimental investigation on the thermal performance of a coiled heat exchanger using a new hybrid nanofluid. Exp Therm Fluid Sci. 2016;76:324–9.
320. Huang D, Wu Z, Sunden B. Effects of hybrid nanofluid mixture in plate heat exchangers. Exp Thermal Fluid Sci. 2016;72:190–6.
321. Bhattad A, Sarkar J, Ghosh P. Discrete phase numerical model and experimental study of hybrid nanofluid heat transfer and pressure drop in plate heat exchanger. Int Commun Heat Mass Transf. 2018;91:262–73.
322. Bhattad A, Sarkar J, Ghosh P. Experimentation on effect of particle ratio on hydrothermal performance of plate heat exchanger using hybrid nanofluid. Appl Therm Eng. 2019;162:114309.
323. Bhattad A, Sarkar J, Ghosh P. Hydrothermal performance of different alumina hybrid nanofluid types in plate heat exchanger. J Therm Anal Calorim. 2020;139:3777–87.
324. Kumar V, Sarkar J. Numerical and experimental investigations on heat transfer and pressure drop characteristics of Al_2O_3-TiO_2 hybrid nanofluid in minichannel heat sink with different mixture ratio. Powder Technol. 2019;345:717–27.