An updated review of nanofluids in various heat transfer devices

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Received: 12 March 2020 / Accepted: 27 April 2020 / Published online: 15 June 2020
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Abstract

The field of nanofluids has received interesting attention since the concept of dispersing nanoscaled particles into a fluid was first introduced in the later part of the twentieth century. This is evident from the increased number of studies related to nanofluids published annually. The increasing attention on nanofluids is primarily due to their enhanced thermophysical properties and their ability to be incorporated into a wide range of thermal applications ranging from enhancing the effectiveness of heat exchangers used in industries to solar energy harvesting for renewable energy production. Owing to the increasing number of studies relating to nanofluids, there is a need for a holistic review of the progress and steps taken in 2019 concerning their application in heat transfer devices. This review takes a retrospective look at the year 2019 by reviewing the progress made in the area of nanofluids preparation and the applications of nanofluids in various heat transfer devices such as solar collectors, heat exchangers, refrigeration systems, radiators, thermal storage systems and electronic cooling. This review aims to update readers on recent progress while also highlighting the challenges and future of nanofluids as the next-generation heat transfer fluids. Finally, a conclusion on the merits and demerits of nanofluids is presented along with recommendations for future studies that would mobilise the rapid commercialisation of nanofluids.

Keywords Nanofluids · Heat transfer · Nanoparticles · Solar collector · Heat exchangers

Abbreviations

AARS Ammonia absorption refrigeration system
AFM Atomic force microscopy
AG Arabic gum
ANN Artificial neural network
CA Citric acid
CFD Computational fluid dynamics
CHF Critical heat flux
CMC Carboxymethyl cellulose
CNT Carbon nanotubes
COP Coefficient of performance
CPC Compound parabolic collectors
CPU Central processing unit
CTAB Cetrimonium bromide
DAPTC Direct absorption parabolic trough collector
DASC Direct absorption solar collector
DI Deionised
DLS Dynamic light scattering
EDX Energy-dispersive X-ray spectroscopy
ETSC Evacuated tube solar collector
FESEM Field emission scanning electron microscope
FPC Flat plate collector
FTIR Fourier-transform infrared spectroscopy
GNP Graphene nanoplatelets
HPSC Heat pipe solar collector
HPSWH Heat pipe solar water heater
HX Heat exchangers
LFR Linear Fresnel reflectors
MAAFG Microwave-assisted acid-functionalised graphene
MCHS Microchannel heat sink
MLG Multilayer graphene
MWCNT Multiwall carbon nanotubes
nePCM Nano-encapsulated phase change materials

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Introduction

Energy is a very important quantitative property that must be transferred before any system can perform work. The transfer of energy can be done by either work or heat [1]. Heat is transferred from one system to another when there exists a temperature difference between the two systems and travels from high to low temperatures [2]. The science that describes the means and rate in which thermal (heat) energy is transferred is known as heat transfer. Heat transfer applications are experienced in our daily life; the human body, for instance, is constantly emitting heat, and humans adjust their body temperature to suit environmental conditions using clothing. Heat transfer is also used in our buildings to regulate temperature [3] and is necessary for cooking, refrigeration and drying. It is also directly applied in car radiators [4] and for temperature control in electronic devices [5]. Heat transfer is used in solar thermal collectors to convert solar energy to heat and power [6, 7] and used in thermal control elements in spacecraft [8]. In many of these devices, heat needs to be dissipated at a rapid rate to ensure effective operation and maximum efficiency within the system [9]. As technology evolves, devices have become smaller and thus require better thermal management. Essentially, the more compact the size, the larger the requirement for effective cooling technology [10]. Therefore, heat transfer enhancement is a very important area in thermal engineering.

Several techniques have been considered to improve the heat transfer coefficient between the working fluids and the fluid contact surfaces [11, 12]. Conventional heat transfer fluids such as water, thermal oils and ethylene glycol/water have some limitations as their thermal properties are quite low when compared to those of solids, as shown in Fig. 1. The improvement in the thermal properties of these fluids through the addition of nanoscaled particles has led to an evolution in the study of heat transfer fluids. The suspension of these solid particles in the base fluid enhances the energy transmission in the fluid leading to improved thermal conductivity properties and better heat transfer characteristics [13]. The resultant fluids have been seen to possess higher values of thermal conductivity [14, 15]. Choi and Eastman [16] were the first to name such fluids as nanofluids. Nanofluids are the engineered colloidal suspension of nanoscaled particles (10–100 nm) in a base fluid [16]. These particles are generally metals, metallic oxides or other carbon-based elements. Over a century ago, Maxwell [17] was the first to discuss the suspension of micro-scaled particles into a fluid. However, microparticles settled rapidly in the fluid leading to abrasion and clogging in the flow channel, limiting further research into suspensions in fluids. Furthermore, these fluids did not exhibit the significant enhancement witnessed today with the use of nanofluids. The introduction of nanoparticles has allowed for further investigation into colloidal dispersion in fluids. Nanoparticles are more stable when dispersed in fluids and tend to improve on the thermal properties of the fluids. Some other properties of nanofluids which make them adequate heat transfer fluids include the Brownian motion of particles, particle/ fluid nanolayers and their reduced pump power when compared to pure liquids to achieve intensified heat transfer.

Despite these benefits, nanofluids still possess some application-based limitations. Issues of sedimentation and aggregation in the fluid have been raised, although the use of ultrasonication, pH modulation, magnetic stirring and the addition of surfactants has been recorded to improve the stability of the nanofluids [18]. Also, increasing the fluid circulation rate in the device reduces the possibilities of sedimentation, although this can lead to an erosion of heat transfer in the device or flow stream. Particles of larger sizes also tend to clog the flow channel, and there have been cases of pressure loss recorded in some devices due to the marginal increase in viscosity. Nanofluids are also expensive to prepare and toxic due to the reactive nature of the nanoparticles [19]. Over the past decade, emphasis on nanofluids research has been more apparent as shown in Fig. 2, which illustrates the number of publications involving nanofluids since 2010. These studies include those related to their preparation, characterisation, measurement of their physical properties and their utilisation in various applications. The data presented in Fig. 2 were obtained by searching the word “nanofluids” in the Scopus database against titles, abstracts and keywords over the period presented. The search illustrates that approximately 3165 papers were published in 2019 alone, and this trend is expected to increase in the coming years. Incidentally, several
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Fig. 1 Bulk material thermal conductivity difference between 
a commonly used base fluids and b commonly used nanoparticles

Fig. 2 Nanofluids-related publication in the past decade

Publications on nanofluids over the past decade
Review papers related to the heat transfer properties and application of nanofluids were published in 2019. The reviews include solar collector applications [20, 21], a review of nanofluids in heat exchangers [22, 23], review of nanofluids in heat pipes [24], radiator cooling [25], electronic cooling [5] and also a review on various thermophysical properties of nanofluids [26, 27]. A list of some of the review papers published in 2019 is listed in Table 1.

Owing to the increasing number of studies relating to nanofluids, there is a need for a holistic review of the progress and steps taken in 2019 concerning their application in heat transfer devices. This study adopts a retrospective look at the year 2019 by reviewing the progress made in the area of nanofluids preparation, nanofluid thermophysical properties measurements and the applications of nanofluids in various heat transfer devices including solar collectors, heat exchangers, refrigeration systems, radiators, thermal storage systems and electronic cooling. The study aims to update readers on recent progress in nanofluid synthesis and application. The study also seeks to highlight the challenges and prospects of nanofluids as the next-generation heat transfer material.

### Preparation of nanofluids

The method used in the preparation of nanofluids is important in the study of the stability and thermophysical behaviour of nanofluids [57]. The preparation steps are also vital in estimating the degree to which the nanofluids are employed in heat transfer systems [58], [59]. In this section, the studies related to nanofluid stability and their synthesis techniques are discussed. Nanofluids are produced by suspending particles of nanosize dimensions in the traditional heat transfer fluids such as water, oils, acetone and glycols [60]. A wide range of nanoparticles have been utilised in the formation of nanofluids, some of these include:

### Table 1

| References | Application reviewed                                                                 | Number of reviewed papers |
|------------|--------------------------------------------------------------------------------------|---------------------------|
| [28]       | Nanofluids in solar dish concentrators                                                | 125                       |
| [29]       | Enhancement of solar energy systems                                                   | 133                       |
| [30]       | A 10-year review of nanofluids in solar thermal collectors, hybrid PV/T and direct steam generation | 100                       |
| [31]       | Performance of solar collectors using carbon-based nanofluids                        | 130                       |
| [32]       | Performance of PVT systems using nanofluids                                          | 178                       |
| [33]       | Nanofluids in heat exchangers for energy savings                                     | 320                       |
| [34]       | Hybrid nanofluids in solar collectors                                                | 187                       |
| [35]       | Nanofluids in solar collectors                                                       | 204                       |
| [36]       | Application of carbon-based nanofluids in heat exchangers                            | 152                       |
| [37]       | Effect of using nanofluids in several types of heat pipes                            | 73                        |
| [38]       | Review of experimental studies using nanofluids in heat pipes                        | 127                       |
| [39]       | Hybrid nanofluids in solar collectors                                                | 261                       |
| [40]       | Review of heat pipe using mono and hybrid nanofluids as working medium               | 113                       |
| [41]       | Factors affecting the use of nanofluids in flat plate solar collectors                | 116                       |
| [42]       | Review of nanofluids in solar collectors                                             | 93                        |
| [43]       | Water-based nanofluids in PVT                                                       | 39                        |
| [44]       | Thermal enhancement of parabolic through collectors using nanofluids                 | 87                        |
| [45]       | Nanofluids in automobile cooling                                                     | 172                       |
| [46]       | Nanofluids used for direct absorption solar collectors                                | 76                        |
| [47]       | Nanofluids in concentrating solar collectors                                         | 140                       |
| [48]       | Application of nanofluids in solar collectors, heat exchangers and radiators         | 108                       |
| [49]       | Nanofluids in flat plate solar collectors                                            | 105                       |
| [50]       | The effect of nanofluid fuels on compression ignition engines                         | 73                        |
| [51]       | Nanofluids in double-pipe heat exchangers with twisted tape                          | 53                        |
| [52]       | Concentrating solar collectors                                                       | 123                       |
| [53]       | Nanofluids in parabolic trough collectors                                            | 192                       |
| [54]       | Nanofluids in thermal photovoltaic systems                                           | 55                        |
| [55]       | Nanofluids in car radiators                                                          | 93                        |
| [56]       | Nanofluids in phase change materials                                                 | 135                       |
(1) Carbon nanoparticles (such as MWCNT, SWCNT, Gn, GO, graphite, diamond and fullerene).
(2) Metal nanoparticles (such as Ag, Al, Au, Co, Cu and Fe).
(3) Metal oxide nanoparticles (such as Al₂O₃, CeO₂, CuO, Fe₃O₄, TiO₂ and ZnO).
(4) Others (such as Si, AlN-C, CoFe₂O₄, SiC, Field’s alloy nanoparticles, ZnBr₂ and SiO₂).

Nanofluids can be unstable due to the strong Van der Waals interactions and cohesive forces between nanoparticles. Therefore, the preparation technique used is extremely important in others to break down these forces and produce stable nanofluids. Different methods have been used to avoid nanoparticle agglomeration and improve the stability of nanofluids, such as pH control, surfactant addition, ultrasonic agitation, magnetic stirring, functionalisation and high-pressure homogenisation [61]. According to Yu and Xie [61], there are three main methods used for nanofluids preparation: one-step chemical technique, one-step physical technique and two-step technique.

The two-step technique is the most widely used for nanofluid preparation, and it is more economical for mass production. In this method, the industrial or laboratory-synthesised nanoparticles are dispersed in the base fluids by agitation, stirring or ultra-sonication [60]. A significant drawback of this technique is it often has low stability and a high tendency of agglomeration. To avoid this problem, several additional techniques, including one-step synthesis techniques and green synthesis techniques, have been used. The two-step nanofluid preparation technique is illustrated in Fig. 3.

Asadi et al. [62] prepared MWCNT/water nanofluid by implementing the two-step method without using surfactants, and both agitation and ultra-sonication were used in the nanofluid preparation. Their nanofluid was stable for one month. However, with the addition of surfactants, Chen et al. [63] adopted the two-step method to prepare MWCNT/DI water using polyvinylpyrrolidone (PVP) as a surfactant. They performed ultra-sonication for only one hour, and they obtained a stable solution for more than two months. Additionally, Almanassra et al. [64] used the two-step method to investigate the stability and thermophysical properties of MWCNT/water nanofluids using different surfactants PVP, SDS and AG. They prepared the nanofluids using ultra-sonication for 30 min, and the solutions were stable for more than six months. Other studies have used different surfactants such as SDBS, CTAB, oleic acid, ethyl carbamate, PEG, EBT, oleylamine, citric acid, Tween 80, Gemini’s and APTMS. The use of surfactants depends on the nature of the base fluid and type of nanoparticles. The surfactants act as a bridge between the base fluids and the nanoparticles. It increases the repulsive forces between the particles and decreases the interfacial tension between the base fluids and suspended nanoparticles. Surfactants also increase the zeta potential of nanoparticles and increase the hydrophilic properties of the suspended particles. Surfactants are classified based on the charge of their head group. Therefore, the surfactants might be cationic (positively charged) such as CTAB, distearyl dimethylammonium chloride and benzalkonium chloride; non-ionic (uncharged, neutral) such as oleic acid, PVP, AG, Tween 80 and oleylamine; anionic (negatively charged) such as SDBS and SDS; and amphoteric (negatively and positively charged) such as lecithin.

Hydrophobic materials are generally chemically or physically pre-treated to improve the particle’s hydrophilicity and their stability in the base fluids. Liu et al. [65] used the two-step method to prepare GO/water nanofluids with particle concentration of (1–4.5 mg mL⁻¹). GO was initially prepared from graphite using the Hummers method; then, nanofluids were prepared using both agitation and ultra-sonication for 40 min and 1 h, respectively. The nanofluids showed good stability for more than three

Fig. 3 Two-step method of preparing nanofluids. (modified from [33])
months. Albert et al. [66] used the sol–gel method using PVA as a surfactant to prepare CuO/water nanofluids. The nanofluids were ultra-sonicated for 1.75 h and remained stable for more than a year. Yang et al. [67] investigated TiO2/water and Ag/water nanofluids for heat recovery using the two-step method of nanofluid preparation. The particles were prepared using the post-treated optimised preparation method, which involves separating the agglomerated particles and studying the stability and heat recovery of the remaining concentration of nanoparticles. The nanofluids prepared using this method were stable for more than six months.

In the single-step method, both steps, (i) formation of particles and (ii) dispersing them in the base fluids, happen simultaneously. In this method, all the intermediate processes such as storage, drying, dispersion of particles and transportation are subtracted or avoided, so the accumulation of nanoparticles decreased, and stability of nanofluids is maximised. Huang et al. [68] adopted the single-step method to prepare ethyl carbamate-modified Field's alloy/polyalpaholefin (PAO) oil nanofluids using the nano-emulsification technique. In this technique, the Field's alloy nanoparticles are heated up to 180 °C in the PAO oil under stirring for 3 h. The nanofluids were considered ready by observing the colour change from white to dark grey. According to the UV–Vis spectra results and zeta potential values, the nanofluids remain stable for more than 3 h.

Moreover, Du et al. [69] considered the one-step method to produce Gn/water nanofluids based on the shear exfoliation of graphite with the help of PVA surfactant. In this method, the graphite was converted to graphene within the DI water by six exfoliation processes. The authors observed a stable solution for more than 180 h by monitoring the UV–Vis spectra. Additionally, Li et al. [70] prepared silver and gold water-based nanofluids using the one-step method. The authors examined the effect of spacer length of different Gemini surfactants on the stability of silver and gold nanofluids. Furthermore, silver and gold solutions were added to the pre-prepared surfactant solution with the addition of glucose and sodium hydroxide under vigorous stirring till a red colour was observed. According to their stability study, the solutions remained stable for more than 60 days.

The one-step method can be used only in small-scale production. Using this method can produce well uniform dispersed nanofluids, although it is costly, and not all types of nanofluids can be produced by this method. For the readers’ convenience, the authors have summarised some of the works on nanofluids preparation in the year 2019 in Table 2. The table summarises the nanoparticles types, base fluids and the methods used for the nanoparticles and nanofluids synthesis, characterisation and stability measurement.

Properties of various nanofluids

The thermophysical behaviour of nanofluids directly affects the application of nanofluids, especially concerning heat transfer. Properties such as the viscosity, thermal conductivity, density and the specific heat capacity of the fluid are all vital in determining the effectiveness of nanofluids as heat transfer fluids. Experimentally, certain techniques and standards have been used in measuring the various thermophysical properties of nanofluids.

The three main techniques in measuring the thermal conductivity of nanofluids are the transient technique, steady-state technique and the thermal comparator [98]. The transient technique is more accurate and reliable than the steady-state technique, as it completely reduces the effect of natural convection and radiation [99]. Rotational viscometers are the main type of instruments used to measure the viscosity of nanofluids. These viscometers do not only measure the viscosity of the fluid, but they can also determine the rheological behaviour of the fluids. On the other hand, the specific heat capacity of nanofluids is usually measured by applying the differential scanning calorimetry (DSC) as it is easy to use, provides adequate accuracy and the measurement times are short. While there have been many studies that measured nanofluids thermophysical properties using the outlined techniques, many other researchers have focused their studies on proving an accurate theoretical model to predict the thermophysical behaviour on nanofluids.

Before the invention of nanofluids, several scientists have theorised the effect of particle dispersion on the thermophysical properties of conventional heat transfer fluids. As previously stated, J. C. Maxwell theorised the thermal conductivity of particle dispersions in a liquid in 1881 [17]. Later, Einstein theorised the dynamic viscosity of particle dispersions in a liquid in 1905. Both research endeavours represent the earliest postulations of the thermophysical behaviour of suspensions in fluids [100]. Several other researchers have proposed models to predict these thermophysical behaviours of suspensions in fluids. Theoretical models developed before the classification of nanofluids are known as classical models. Table 3 illustrates the classical models for predicting the thermophysical properties of nanofluids. While the classical models were accurate to a limited range, the models often did not predict the values of thermal conductivity, viscosity and specific heat capacity of the nanofluid with high enough levels of accuracy. This is mainly because, in the nanoscale, previously unconsidered factors appear to affect the thermophysical properties of fluid dispersion, while most classical models considered volume concentration and the base fluid property as the most important.
### Table 2 Review of some 2019 studies on the synthesis, preparation, characterisation and stability methods of nanofluids

| References          | Material of nanoparticles | Base fluid | Nanoparticles synthesis method | Nanoparticles/characterisation | Nanofluid preparation method | Stability study method | Surfactant | Stirring time/min | Sonication time/h | Stability duration/day |
|---------------------|---------------------------|------------|--------------------------------|--------------------------------|-------------------------------|-----------------------|------------|------------------|-------------------|----------------------|
| Albert et al. [66]  | CuO                        | DI water   | Sol–gel method                | FTIR, XRD, TEM, FESEM, UV–Vis | One-step and two-step methods | Zeta potential, UV—Vis, TEM, DSC–TG | PVA        | 1.75              | 40                | 60 min               | > 90                 |
| Liu et al. [65]     | GO                         | Water      | Modified Hummers method       | TEM, FESEM, UV–Vis, XRD, DLS | Two-step                     | Visual observation     | –          | –                | 120               | 60                   | 30                  |
| Asadi et al. [62]   | MWCNT                      | Water      | –                              | XRD                            | Two-step                     | Visual observation     | –          | –                | –                 | –                    | –                   |
| Rostami et al. [71] | GO, CuO (50:50)            | Water–EG   | –                              | FESEM, XRD                      | Two-step                     | DLS                   | –          | –                | 60                | –                    | –                   |
| Almanassra et al. [64] | MWCNT                  | Water      | –                              | TEM                            | Two-step                     | Zeta potential, visual observation | SDS, PVP, AG | –                | 0.5               | > 180                |                     |
| Chen et al. [63]    | MWCNT                      | DI water   | –                              | TEM, SEM, DLS                  | Two-step                     | Zeta potential, UV–Vis, PVP and acid treatment | Used for the mechanical method | –                | –                | –                 | –                    | –                   |
| Nithiyanantham et al. [72] | Al₂O₃, SiO₂ | NaNO₃ and KNO₃ | –                              | –                              | A dry preparation method based on a mechanical mixing | SEM and X-ray powder diffraction (XRPD) | Mechanical stirring | –                | –                | –                 | –                    | –                   |
| Mahyari et al. [73] | GO–SiC 50:50               | Water      | –                              | SEM, XRD                        | Two-step                     | DLS                   | –          | –                | 60                | 0.75                 | –                   |
| Palanisamy et al. [74] | MWCNT                  | Water      | –                              | XRD                            | Two-step                     | TEM                   | SDBS       | 5                | –                 | 45                  |                     |
| Kiaee et al. [75]   | SiO₂, CuO                  | Water      | Sol–gel process and impregnation | TEM, SEM, XRD, small-angle X-ray scattering (SAXS) | Two-step                     | Visual observation     | CTAB       | 120              | 1                 | 11                  |                     |
| Gulzar et al. [76]  | Al₂O₃, TiO₂                | Therminol-55 | Ball mill                      | TEM, SEM, EDX                  | Two-step                     | Zeta potential, Oleic acid | –          | –                | 240              | 2                   | > 7                 |
| Prasad et al. [77]  | SiO₂                       | Glycerol, water | –                              | SEM                            | Two-step                     | Zeta potential, Oleic acid | –          | 60                | 2                 | –                   | –                   |
| Huang et al. [68]   | Field’s alloy nanoparticles| Polyalphadefin (PAO) oil | Nano-emulsification technique | DLS, AFM, DLS zeta potential analyser | One-step                     | UV–Vis                | Ethyl carbonate | 180              | 5–10 min.          | > 0.21              |
| Bin-Abdun et al. [78]| CuO                      | Water      | –                              | SEM                            | Two-step                     | Visual observation     | SDS        | 180              | 12                | 4                   |                     |
| References          | Material of nanoparticles | Base fluid     | Nanoparticles synthesis method | Nanoparticles characterisation | Nanofluid preparation method | Stability study method | Surfactant | Stirring time/min | Sonication time/h | Stability duration/day |
|---------------------|---------------------------|----------------|-------------------------------|-------------------------------|-------------------------------|------------------------|-------------|------------------|-----------------|---------------------|
| Taghizadeh et al. [79] | CeO₂                     | EG, DI water  | –                             | SEM, FTIR, XRD, EDX          | Two-step                      | Zeta potential          | CTAB        | –                | 5               | > 21                |
| Liu et al. [80]     | Al₂O₃, CuO, ZnO, Al, Cu  | Paraffin wax  | –                             | SEM                          | Two-step                      | UV–vis–spectrophotometry  | –           | 10               | 1–5             |                     |
| Rukman et al. [81]  | TiO₂, MWCNT               | Water         | –                             | –                            | Two-step                      | –                      | –           | –                | –               | –                   |
| Yang et al. [67]    | TiO₂, Ag                  | DI water      | Post-treated optimised preparation method | –                            | Two-step                      | UV–Vis                 | –           | –                | –               | < 6                 |
| Syarif et al. [82]  | Al₂O₃                    | Water         | Self- combustion method       | TEM, FTIR, XRD               | Two-step                      | Zeta potential          | PEG         | –                | 2               | –                   |
| Kharat et al. [83]  | CoFe₂O₄                  | EG            | Co- precipitation wet chemical technique | FESEM, XRD, EDS and VSM techniques | Two-step                      | –                      | –           | 3                | –               | –                   |
| Wang et al. [84]    | Modified Field’s alloy nanoparticles | PAO oil | Facile one-step nanoemulsion method using as a surfactant | TEM, FTIR | Two-step | Zeta potential | Ethyl carbonate | –        | 0.5              | > 30             |                     |
| Barai et al. [85]   | GO, Fe₃O₄                | Water         | Hummer’s method               | TEM, XRD, UV/Vis, Raman, XPS analysis | Two-step                      | –                      | –           | –                | –               | –                   |
| Afzal et al. [86]   | ZnO, CuO                 | DI water      | –                             | FTIR                         | Two-step                      | Zeta potential UV–Vis   | EBT and OA (oleylamine) | 35           | 2–8              | 74               |
| Nithiyanatham et al. [87] | SiO₂, Al₂O₃            | NaNO₃–KNO₃   | Wet chemical route method     | TEM, SEM, FTIR, XRD         | One-step                      | Visual observation       | –           | 15               | –               | 1                   |
| Du et al. [69]      | Gn                       | Water         | Shear exfoliation of graphite | SEM, UV–Vis, Raman          | One-step                      | UV–Vis                 | PVA         | –                | –               | > 7.5               |
| Abadeh et al. [88]  | Fe₃O₄                   | Water         | Grinding                      | TEM, DLS                     | Two-step                      | Zeta potential, vibrating sample magnetometer (VSM) | CA, GA, SDS DBS, C-tab and Tween 80 | 5         | 0.3–1            | –               | –                   |
| References                  | Material of nanoparticles | Base fluid | Nanoparticles synthesis method | Nanoparticles/characterisation | Nanofluid preparation method | Stability study method | Surfactant | Stirring time/min | Sonication time/h | Stability duration/day |
|-----------------------------|---------------------------|------------|-------------------------------|-------------------------------|-----------------------------|-----------------------|------------|-------------------|------------------|----------------------|
| Li et al. [70]              | Au, Ag                    | Water      | –                             | TEM, UV–Vis                  | One-step                    | Zeta potential         | Gemini     | 60                | –                | > 60                  |
| Mahbubul et al. [89]        | Al2O3                     | Distilled water | –                             | –                             | Two-step                    | Liquid density         | –          | –                 | 1–5              | 20                   |
| Wajri et al. [90]           | CuO                       | EG         | Wet chemical (precipitation) method | TEM, FTIR, XRD, UV–Vis       | Two-step                    | Visual observation     | –          | –                 | –                | 4                    |
| Nazarzade et al. [91]       | Ag                        | Water      | Reduction method              | TEM, DLS, UV–Vis             | Two-step                    | –                     | –          | –                 | –                | –                    |
| Prasad et al. [92]          | Co, SiO2                  | Glycerol, water | –                             | SEM                           | Two-step                    | Zeta potential         | –          | 30                | 2                | 60                   |
| Chen et al. [93]            | Al2O3                     | Paraffin   | –                             | DLS                           | Two-step                    | Zeta potential          | Oleic acid | 30–45             | 2.75–3.5         | < 60                  |
| Esmaeili et al. [94]        | AlN-C                     | EG         | Green, facile and inexpensive mechanochemical route | TEM, SEM, XRD, DLS, DTG-TGA | Two-step                    | Zeta potential, FTIR, NMR, UV–Vis | – | 60               | 0.5              | > 90                  |
| Prasad et al. [95]          | Co                        | Glycerol, water | –                             | SEM                           | Two-step                    | Zeta potential          | visual observation | –                 | 2                | > 50                  |
| Mohammed et al. [96]        | ZnBr2, ZnO                | Acetone    | –                             | –                             | Two-step                    | TEM, visual observation | PVA, PVP, SDS        | –                 | 0–24             | 0.17                  |
| Graves et al. [97]          | Cu                        | Methanol   | –                             | DLS                           | Two-step                    | Zeta potential          | visual observation | –                 | 0.5              | 180                  |
variables in determining the thermophysical properties as Einstein described it as “small rigid spheres suspended in a liquid”. However, research deduced that nanofluids thermophysical properties are affected by a broader range of variables which include particle size [101], volume concentration, base fluid property, particle agglomeration, packing fraction, fluid pH, nanolayers, particle distribution, temperature and mixture ratio (hybrid nanofluids). The inability of the classical models to factor in these variable conditions limits its application to only a narrow range of values.

The physical properties of the nanofluids are an important parameter in predicting the heat transfer and friction factor behaviours of individual nanofluids. Mahian et al. [108], summarised the computational methods for solving the thermal transport model for nanofluids flow. These methods include the finite difference method, finite volume method, finite element method, lattice Boltzmann methods and other Lagrangian methods such as dissipative particle dynamics and molecular dynamics. Based on experimental results, Dadhich et al. [109] used the artificial neural network to develop correlations used to predict the heat transfer coefficient of Al₂O₃ and TiO₂ water-based nanofluids flowing in an annulus at 1 bar. The three input parameters used in their study were nanoparticle concentration, heat flux and mass flux. Their results show that both nanofluids performed better than water. At a nanoparticle concentration of 0.2%, Al₂O₃ nanofluid had enhancement of 155.24% and TiO₂ nanofluid had a heat transfer coefficient increase of 71.56% as compared to that of water. The heat transfer and friction factor behaviour hybrid nanofluids have also been investigated. Yang et al. [110] investigated the dynamic stability, sedimentation and time-dependent heat transfer characteristics of TiO₂ and CNT nanofluids. They discovered that for a volumetric concentration of 0.3% TiO₂ and 0.1% CNT nanofluids, the convective heat transfer coefficient is increased by 17.84% and 19.31%, respectively. Hameed et al. [111], from experimental data, compared the heat transfer and pressure drop behaviour of alumina–CNT/water nanofluids and alumina–Cu/water nanofluids. The convective heat transfer enhancement of alumina–CNT/water was higher compared to alumina–Cu/water hybrid fluid. The maximum enhancements of 30.65% and 20.48% in Nusselt number were obtained at 0.3% volume fraction of alumina–CNT/water and alumina–Cu/water hybrid nanofluid, respectively. Their study provided experimental correlation for both fluids.

### Thermal conductivity of nanofluids

Yu et al. [112] conducted a review over a decade ago to compare the thermal conductivity of nanofluids and their convective heat transfer enhancement. They concluded that from 107 works of literature surveyed, a 15–40% enhancement was recorded with the oxides nanoparticles available back then. Today, numerous research investigating the use of different nanoparticles on the thermal conductivity has been conducted. Esfe and Afrand [113] extensively covered the thermal conductivity of nanofluids that predate 2019. In 2019, as it has been the trend, a majority of the studies focused on hybrid nanofluids. Akhgar et al. [114]...
experimentally measured the thermal conductivity of MWCNT–TiO$_2$/ethylene glycol nanofluid and obtained that an increase in volume concentration of the nanofluid tends to increase the thermal conductivity of the hybrid nanofluid. The study considered volume concentration between 0.05 and 1% and observed that at a volume concentration of 1%, maximum enhancement (40.1%) in thermal conductivity was obtained. The study also developed an artificial neural network (ANN) model to predict the thermal conductivity values obtained from the experiment. Also, Alarifi et al. [115] developed an ANN model from their experimental results to predict the thermal conductivity of MWCNT–TiO$_2$/thermal oil nanofluid.

As shown in Table 4, while many studies have begun to use the artificial neural network (ANN) models in thermal conductivity prediction, some others have proposed regression-based correlation equations to fit results obtained from their experiments. Moldoveanu et al. [116] conducted an experimental study on the thermal conductivity variation of Al$_2$O$_3$–TiO$_2$/water nanofluid at volume concentration between 0.25 and 1% and proposed a correlation model to predict the thermal conductivity.

In terms of unique conventional nanofluids, Essajai et al. [117] studied the effect of particle shape on the thermal conductivity of nanofluids. The study was performed using a one-dimensional (1-D) network of interconnected gold nanoparticles (AuNPs) and spherical Au nanoparticles. It was observed that AuNPs in base fluids were more effective in improving the thermal conductivity of nanofluids than spherical Au particles suspended in a base fluid. Applying the one-step synthesis technique, the stability and the thermal conductivity measurement of MWCNTs/Jatropha seed oil nanofluid were investigated [118]; this environment-friendly nanofluid showed a thermal conductivity enhancement of 6.76% at a mass concentration of 0.8%.

ANN has also been used to predict the effect of particle aggregation on the thermal conductivity of nanofluids [119]. Mirsaeidi and Yousef [120] used ANN to predict the thermal conductivity, density and viscosity of carbon quantum dots nanofluids using water, ethylene glycol and EG–water (60:40) as base fluids. Motlagh et al. [121] used gene expression programming to propose a correlation that estimates the thermal conductivity of Al$_2$O$_3$ and CuO–water-based nanofluid based on experimental data from the literature. Going forward, it is expected that there will be an increase in research and development exploring the possible advantages of using ternary hybrid nanofluids. In this regard, the study conducted by Mousavi et al. [122] has already demonstrated that the thermal conductivity of CuO–MgO–TiO$_2$/water nanofluid is enhanced by 78.6% at a mass fraction of 0.1. For the reader’s convenience, the authors have summarised the work on thermal conductivity studies for hybrid nanofluids in the year 2019 in Table 4.

### Viscosity of nanofluids

The viscosity of a fluid is important in understanding both the heat transfer and the flow behaviour of the fluid. Several experimental studies have been carried out to understand the behaviour of nanofluids. The available research on the topic is not limited to experiments alone as molecular dynamics simulations have also been used to explain the viscosity of nanofluids [136]. Dehghani et al. [137] analysed the effect of temperature and mass fraction of Al$_2$O$_3$ and WO$_3$ nanoparticles in water and liquid paraffin. Their findings showed that the viscosity of both nanofluids is increased only by adding a certain number of nanoparticles to both fluids. Regarding the shear rates, the viscosity of water-based nanofluids is constant, which indicates a Newtonian behaviour, while that of paraffin does not remain constant at different shear rates, and at a low amount of shear rate the viscosity achieves higher value, indicating a non-Newtonian behaviour for liquid paraffin-based nanofluids. Finally, they presented a correlation based on temperature, nanoparticle concentration and the physical properties of both the nanoparticle and base fluid for predicting the viscosity of aqueous and non-aqueous nanofluids. Ye et al. [138] extensively covered the viscosity of nanofluids that predate 2019. In 2019, as with thermal conductivity studies, there has been a trend towards hybrid nanofluids. The significance of viscosity in lubrication applications has been seen in many investigations related to oil-based nanofluids. Using the ultrasonic-assisted process, Barai et al. [85] synthesised graphene oxide–Fe$_3$O$_4$/water nanofluid at volume concentrations between 0.01 and 0.2%. The study obtained a maximum viscosity enhancement of 41%. Studying Fe–CuO/EG–water nanofluid, Bahrami et al. [139] obtained that the backward propagation methods presented the least error in predicting dynamic viscosity. Bahrami et al. [139] deduced that when the hybrid nanofluids volume concentration is below 0.1%, the Fe–CuO/EG–water nanofluid exhibited Newtonian behaviour. However, when Fe–CuO/EG–water nanofluid volume concentration is above 0.25% the behaviour of the fluid changed.

As shown in Table 5, while many studies have proposed various correlation models to predict the viscosity behaviour of nanofluids, the more accurate models proposed are the artificial neural network (ANN) models. Ruhani et al. [140] investigated the effects of volume concentration and fluid temperature on the viscosity of hybrid nanofluids. The correlation model proposed in this study demonstrated a 1.8% margin of deviation between experimental values and correlation results. Viscosity enhancement was about 80% when the volume fraction was 2%.

Other types of conventional nanofluids were also studied; Mousavi et al. [141] conducted an experimental investigation into the viscosity measurements of MoS$_2$/diesel oil nanofluid at particle concentration between 0.1 and 0.7%. The study
| References                      | Particle A | Particle B | Size particle A       | Size particle B | Base fluid          | Concentration       | Predictive model     | Thermal conductivity enhancement/ % |
|--------------------------------|------------|------------|-----------------------|-----------------|---------------------|---------------------|----------------------|-----------------------------------|
| Akhgar et al. [114]            | MWCNTs     | TiO₂       | Outer diameter 20–30 nm, inner diameter 5–10 nm | 30              | Water/EG (50:50)    | 0.05–1%             | Levenberg–Marquardt ANN       | 40.1                              |
| Taherialek-ouhi et al. [123]   | Graphene oxide | Al₂O₃      | 3.4–7 (thickness)     | 20              | Water               | 0.1–1%              | Correlation equation         | 39.3                              |
| Nithiyanan-tham et al. [87]    | SiO₂@ Al₂O₃ core–shell | Al₂O₃ | 12–17 outer shell thickness 2–5 nm | Molten salt | 1%                  | NA                  | Correlation equation         | 19                                |
| Alarifi et al. [115]           | MWCNT      | Al₂O₃      | Outside diameter 20–30 nm; inside diameter 5–10 nm | 20              | Thermal oil         | 0.125–1.5%          | ANFIS-ANN                      | 45                                |
| Akilu et al. [124]             | SiC        | CuO/C      | 45–65                 | 22–35           | EG                  | 0.5–3.13%           | Correlation equation         | 19.3                              |
| Shahsavari et al. [125]        | CNT        | Fe₂O₃      | Outer diameter 10–30 nm and length 10 μm | NA              | Water               | 0.2–2.25%           | Correlation equation         | 46                                |
| Okonkwo et al. [114]           | Al₂O₃      | Fe         | 29                    | 46              | Water               | 0.05–0.2%           | NA                   | 14                                |
| Arani and Pourmogh-adam [126]  | MWCNTs     | Al₂O₃      | Outside diameter: 5–15 nm, Inside diameter: 3–5 nm, Length: ~ 50 nm | 20              | EG                  | 0.02–0.8%           | Correlation equation         | 17                                |
| Arasu et al. [127]             | TiO₂       | Ag         | NA                    | NA              | Water               | 0.15 vol%           | NA                  | 12.2                              |
| Moldoveanu et al. [116]         | Al₂O₃      | TiO₂       | 43                    | 30              | Water               | 1.0–3.0%           | Correlation equation         | 19.2                              |
| Rubasingh et al. [128]          | TiO₂       | ZnO        | NA                    | NA              | EG                  | 1–8%                | Correlation equation         | 33                                |
| Sulgani and Karimipour [129]   | Al₂O₃      | Fe₂O₃      | 20                    | 20–40           | 10w40-engine oil    | 0.25–4%             | Correlation equation         | 33                                |
| Mousavi et al. [130]            | MgO        | TiO₂       | 25–45                 | 18–23           | Water               | 0.1–0.5 Vol%        | Correlation equation         | 35                                |
| de Oliveira et al. [131]        | Diamond    | Ag         | NA                    | NA              | EG                  | 0.005–0.1%          | Correlation/ ANFIS/ ANN       | 7                                 |
| Wole-Osho et al. [132]          | Al₂O₃      | ZnO₂       | 29                    | 70              | Water               | 0.3–1.67%           | Correlation/ ANFIS/ ANN       | 40                                |
| Ahmed et al. [133]             | ZnO        | TiO₂       | 17                    | 21              | Water               | 0.1%                | NA                  | 36                                |
| Giwa et al. [134]              | Al₂O₃      | Fe₂O₃      | NA                    | NA              | DI water and EG–DI water | 0.05–0.75%          | ANFIS, ANN, correlation       | 1692.16% and 7618.89% for DI water and EG–DI water, respectively |
| Pourrajab et al. [135]          | MWCNTs     | Ag         | NA                    | NA              | Water               | 0.20%               | Correlation equation         | 47.3                              |
### Table 5  Viscosity studies of hybrid nanofluids in 2019

| References          | Nanofluid type | Particle A   | Particle B  | Size of particle A | Size of particle B | Base fluid      | Concentration | Predictive model | Viscosity enhancement/% | Rheological behaviour |
|---------------------|----------------|--------------|-------------|--------------------|--------------------|------------------|----------------|-------------------|------------------------|------------------------|
| Aghahadi et al. [143] | Hybrid         | MWCNTs       | WO3         | Outer diameter 20–30 nm, inner diameter 5–10 nm | 23–65              | 10W-40 Engine Oil | 0.05–0.6%     | Correlation equation | 15                     | Newtonian behaviour    |
| Akilu et al. [124]  | Hybrid         | SiC          | CuO/C       | 45–65              | 22–35              | EG               | 0.5–3.13%     | Correlation equation | 93                     | NA                     |
| Alarifi et al. [144] | Hybrid         | MWCNTs       | TiO2        | Outer diameter < 7 nm inner diameter 2–5 nm and length 10–30 µm | 40               | 5W50 oil        | 0.25–2%       | Correlation equation | 42                     | Newtonian behaviour    |
| Alarifi et al. [115] | Hybrid         | MWCNT        | Al₂O₃       | Outside diameter 20–30 nm; inside diameter 5–10 nm | 20               | Thermal oil     | 0.125–1.5%    | ANFIS-ANN         | 81                     | NA                     |
| Bahrami et al. [139] | Hybrid         | Fe           | CuO         | 35–45              | 25–55              | Water/EG (20:80) | 0.25–1.5%     | ANN Model         | 2200%                  | Newtonian behaviour; Vol conc < 1.0, Non-Newtonian behaviour; Vol conc > 0.25 |
| Barai et al. [85]    | Hybrid         | Graphene oxide | Fe₃O₄ | NA | NA | Water | 0.01–0.2% | NA | 41 | Non-Newtonian shear thinning behaviour |
| de Oliveira et al. [131] | Hybrid         | Diamond      | Ag          | NA | NA | EG | 0.005–0.1% | NA | 20 |
| Esfe et al. [145]    | Hybrid         | MWCNT        | Al₂O₃       | Outer diameter 5–15 nm, inner diameter 3–5 nm and length 50 µm | 5               | 5W50 oil        | 0.05–1%       | Correlation equation | 24                     | Non-Newtonian behaviour |
| References       | Nanofluid type | Particle A | Particle B | Size of particle A | Size of particle B | Base fluid       | Concentration | Predictive model | Viscosity enhancement/% | Rheological behaviour |
|------------------|----------------|------------|------------|--------------------|--------------------|------------------|---------------|------------------|------------------------|-----------------------|
| Esfe et al. [146]| Hybrid         | MWCNTs     | ZnO        | Outer diameter 5–15 nm, inner diameter 3–5 nm | 10–30              | 10W 40 oil       | 0.05%–1%      | Correlation equation | 29                     | Non-Newtonian fluid of shear thinning behaviour |
| Esfe et al. [147]| Hybrid         | MWCNTs     | TiO₂       | Outer diameter 5–15 nm, inner diameter 3–5 nm | 30                 | SAE50 oil        | 0.0625–1.0%   | Correlation equation | 31                     | Non-Newtonian behaviour |
| Goodarzi et al. [148]| Hybrid         | MWCNTs     | ZnO        | Outer diameter 5–15 nm, inner diameter 3–5 nm and length 50 µm | 35–45              | Engine oil       | 0.05–0.8%     | Correlation equation | 20                     | Newtonian behaviour |
| Kumar and Sahoo [149]| Hybrid         | Al₂O₃      | CuO        | 42                 | 42                 | EG:PG            | 0.1–1.5%      | NA               | 102                    | NA                    |
| Mousavi et al. [130]| Hybrid         | MgO        | TiO₂       | 25–45              | 18–23              | Water            | 0.1–0.5%      | Correlation equation | 45                     | NA                    |
| Nithiyantham et al. [87]| Hybrid         | SiO₂@Al₂O₃ core–shell | 12–17 outer shell thickness 2–5 nm | Molten salt | 1% | NA | 27 | NA | NA | NA |
| Okonkwo et al. [14]| Hybrid         | Al₂O₃      | Fe         | 29                 | 46                 | Water            | 0.05–0.2%     | NA               | 55                     | Newtonian behaviour |
| Ruhani et al. [140]| Hybrid         | ZnO        | Ag         | 10–30              | 30–50              | Water            | 0.125–2%      | Correlation equation | 80                     | NA                    |
| Shahsavvar et al. [93]| Hybrid         | CNT        | Fe₂O₄      | Outer diameter 10–30 nm and length 10 µm | NA                 | Water            | 0.2–2.25%     | Correlation equation | 93                     | NA                    |
observed that the viscosity increased by 7.04% when volume concentration was 0.7%. Hameed et al. [142] synthesised an eco-friendly MWCNTs-Kapok seed oil nanofluid using a one-step method, at a constant nanoparticle concentration of 0.1%.

Considering all of the experimental viscosity measurements conducted, the relationship between viscosity and both temperature and particle concentration is apparent. Naturally, the viscosity of nanofluids increases with an increase in particle concentration, and this is observed in virtually all measured experiments. The viscosity of nanofluids decreases with an increase in temperature, and this is also observed in all measured experiments; this behaviour is expected as entropy is increased as particles gain thermal energy. However, the relationship between particle concentration and rheology is not as apparent. Considering the sample size alone as illustrated in Table 5, it can be observed that there exists no clear pattern between rheological behaviour and particle concentration in nanofluids. Rheological behaviour appears to vary from material to material.

### Specific heat of nanofluids

The specific heat capacity of fluids is important in understanding both the heat transfer and the energy content of thermal systems. While significant research has focused on both viscosity and thermal conductivity, studies relating to the specific heat capacity of nanofluids are not as advanced. However, the specific heat capacity of fluid bears significance in thermal storage applications. Therefore, many studies regarding specific heat capacity often use molten salt as their base nanofluid. Moldoveanu and Minea [153] experimentally measured the specific heat of both Al₂O₃–TiO₂/water nanofluids and Al₂O₃–SiO₂/water nanofluids at volume concentration between 1 and 3.0%.

A correlation model was determined from the measured specific heat capacity values. It is important to note that the correlation model had an average deviation of 11% when compared to experimental specific heat values. However, when the mixture theory model was used to predict the nanofluids’ specific heat capacity values, the deviation was as high as 19%.

The effect of particle size and volume fraction on the specific heat of SiO₂ molten salt nanofluid was investigated by Li et al. [154]. Using SiO₂ nanoparticle with sizes of 10, 20, 30 and 60 nm, SiO₂ molten salt nanofluid was synthesised at particle concentration between 0.5 and 2%. Addition of particles to molten salt increases the specific heat capacity for all of the volume concentrations and particle sizes considered. An important point to note is that the particle concentration and particle size with the most specific heat enhancements were 1% and 20 nm, respectively.
Using SiO₂, Al₂O₃ and TiO₂ nanoparticles, three conventional nanofluids were synthesised by Hassan and Banerjee [155]. The study aimed to predict the specific heat capacity of metal oxide molten nitrate salt nanofluids using a multilayer perceptron neural network (MLP-ANN). The ANN model proposed was more accurate when compared to classical prediction methods [155]. Alade et al. [156] also considered a machine learning approach by applying a support vector regression model optimised with a Bayesian algorithm to predict the specific heat capacity of Al₂O₃ ethylene glycol nanofluids. The proposed model also exhibited a high degree of accuracy with the root-mean-square error (RMSE) equivalent to 0.0047.

From Table 6, while the specific heat of molten salts increases with the addition nanoparticles, in experiments involving MWCNTs PEG 400 nanofluid, Al₂O₃–water nanofluid, Fe–water nanofluid and Al₂O₃–Fe nanofluid the specific heat of the base fluid exceeds that of the nanofluids.

### Factors affecting nanofluids stability and thermophysical properties

The main factors affecting the thermophysical properties of nanofluids includes the morphology and concentration of nanoparticles, aggregation in the nanofluids and the sonication time used in its preparation [158]. The stability of nanoparticles suspended in a fluid is a very important parameter that affects both the rheological and thermophysical behaviours of the resultant nanofluids. Brownian motion causes the particles to collide with one another leading to cluster formation in the base fluid. These cluster formations or aggregation are controlled by a variety of internal forces between the base fluid and the nanoparticles such as the Van der Waals forces of attraction between the particles [159]. The aggregates begin to crystallise as their density exceeds that of the base fluid and affects the stability of the nanofluids over time [152]. Some of the factors that affect the stability of the nanofluids include the method of preparation of the nanofluids [66], agitation and sonication time [160–162], pH of the nanofluids [152], the addition of surfactants [163, 164] and surface charge density of the nanoparticles [158]. Asadi et al. [165] reviewed the effect of sonication on the stability and thermophysical properties of nanofluids. The study concluded that while there exists an optimum sonication time where thermal conductivity is maximum, and viscosity is least, more research is required to determine this optimum value, as it appears to differ for different nanofluids. Khan and Arasu [166] also reviewed the effects of nanoparticle synthesis techniques on the stability and thermophysical behaviour of nanofluids. The study importantly noted that there appears to be no standard method for stability measurements; this makes it difficult to compare stability across different papers. This is a problem because of the significant differences in reported fluid stability; this can range from days in some studies to months in others.

The values of the thermophysical properties of nanofluids are sensitive to the volume and size of nanoparticles used, the temperature of the mixture and the use of surfactants [167]. Yang et al. [168] investigated the thermal conductivity of graphene oxide/water nanofluids with a mass concentration range of 0–1.5%. Their result showed that as the mass fraction of nanoparticles increased, the thermal conductivity enhancement increased. Also, at a pH of 8, the nanofluids showed maximum stability with a maximum thermal conductivity enhancement of 48.1%. This indicated that the pH was a significant parameter in both its stability and thermal conductivity. The authors attributed the thermal enhancement observed to the increased Brownian motion of particles and molecules of the base fluid as temperature increased. Yang et al. [169] also studied the thermal conductivity behaviour of zinc nanopowder in SAE 50 engine oil and recorded an increase in the thermal conductivity of the

### Table 6: Some specific heat studies of nanofluids in 2019

| References                  | Nanofluid type | Particle A | Particle B | Size particle A/nm | Size particle B/nm | Base fluid | Particle concentration | Predictive model          |
|-----------------------------|----------------|------------|------------|---------------------|---------------------|------------|------------------------|--------------------------|
| Mousavi et al. [130]        | Hybrid         | MgO        | TiO₂       | 25–45               | 18–23               | Water      | 0.1–0.5 vol%           | Correlation equation      |
| Okonkwo et al. [14]         | Hybrid         | Al₂O₃      | Fe         | 29                  | 46                  | Water      | 0.05–0.2%              | NA                       |
| Moldoveanu and Minea [153]  | Hybrid         | Al₂O₃      | TiO₂       | 45                  | 30                  | Water      | 1–3.0%                 | Correlation equation      |
| Moldoveanu and Minea [153]  | Hybrid         | Al₂O₃      | SiO₂       | 45                  | 20                  | Water      | 1–3.0%                 | Correlation equation      |
| Marcos et al. [157]         | Conventional   | MWCNT      | NA         | Outside diameter 4–10 nm, length 60–100 nm | NA | PEG400 | 0.01–1.0% | Correlation equation |
nanolubricant as the volume concentration of nanoparticles was increased. They recorded a maximum thermal conductivity enhancement of 8.74% and attributed this to the effects of increased Brownian motion of particles in the lubricant as temperature raises. The thermophoresis effect was another factor they highlighted that affected the thermal conductivity enhancement.

Rostami et al. [71] examined the thermal conductivity of GO–CuO water/EG (50:50) hybrid nanofluid at a temperature of 25–50 °C and particle volume concentration of 0.1–1.6%. Their investigation observes a 46% enhancement in thermal conductivity, which is higher than the enhancement of using single nanomaterial. Mahyari et al. [73] investigated the thermal conductivity GO/SiC (50:50)/water hybrid nanofluid at volume concentrations between 0.05 and 1%. Their investigation reveals that the effect of the volume concentration of nanoparticles was more significant than the effect of increasing temperature. Importantly, the studies observed that the enhancement in thermal conductivity of their hybrid nanofluid was more than the reported thermal conductivity enhancement using GO or SiC individually. Hybrid nanofluids not only affect the thermal conductivity, but also enhance the stability of nanofluids.

**Heat transfer mechanisms of nanofluids**

The main benefit of using nanofluids is their enhanced thermal transport which results in improvements in the thermal conductivity of traditional heat transfer fluids. As previously outlined, several parameters influence the thermal conductivity enhancement and include nanoparticle type, nanoparticles size, nanoparticles concentration, temperature, type of base fluid and the thermophysical properties of both the base fluid and the nanoparticles. Over the last three decades, since the introduction of nanofluids in 1995, the explanations behind the enhanced heat transfer of nanofluids have been attributed to several mechanisms. The size and the large number of particles interacting with the base fluid present a challenge to properly understanding the nanoscale effects that support the improved thermal properties observed in the literature. Mahian et al. [108, 170] studied the mechanisms that would aid the simulation of nanofluids flow. They highlighted that forces such as drag, lift, Brownian motion, thermophoresis, Van der Waals and electrostatic double-layer forces had a significant effect on the thermal and rheological behaviours of nanofluids.

Brownian motion is defined as the uncontrollable random motion of particles within the fluid due to the collision between slow moving and higher velocity particles. Brownian motion occurs as a result of thermal diffusion, and this phenomenon is increased at higher temperatures, low viscosity and smaller particle size. As promoted by the scientific community, the random collision of particles within the fluid remains the primary reason for the thermal conductivity enhancement observed with nanofluids [73, 79, 92]. However, Jang and Choi [171] provided three types of collisions that occur due to the rising temperature of nanofluids: collisions between the molecules of the base fluid, collisions between base fluid molecules and the nanoparticles, and the collisions between nanoparticles due to Brownian motion. They concluded that the effect of Brownian motion on thermal conductivity enhancement had the least effect among the three types of collisions.

Keblinski et al. [172] was the first to introduce the idea of nanolayers and their effect in nanofluid thermophysical behaviour. The nanolayer is known as the solid-like structure or the interfacial layer between the solid surface and the first layer of the fluid in contact with the solid surface. A structured, layered arrangement of the fluid molecules around the surface of the nanoparticles was observed. These layers behaved like solids and act as a thermal bridge for the heat transfer process enhancing the overall thermal conductivity of the fluid. In the solid–solid interface, this layer acts as a barrier of heat transfer due to incomplete contact between solid surfaces. However, it is not the case for the solid–liquid interface as the aligned interfacial shell in the nanoparticle suspension would make heat transfer across the interface effective. Yu and Choi [173] presented a modified Maxwell model to account for the effect of nanolayers on the thermal conductivity of nanofluids. Their results proved that the thermal model is enhanced as a result of accounting for this factor. Xie et al. [174] investigated the effect of the nanolayer on the effective thermal conductivity of nanoparticle–fluid mixtures. It was observed that the effective thermal conductivity increases with a decrease in particle size and an increase in nanolayer thickness. It was concluded that manipulating the nanolayer structure might be an effective method to produce higher thermally conductive nanofluids.

Another factor responsible for nanofluid thermophysical behaviour is the “particle nanoclusters”. It should be noted that nanoparticles have strong Van der Waals interactions that force them to form nanoclusters, which lead to a rich zone of high thermal conductive nanoparticles that improve the bulk thermal conductivity of the fluid. However, increasing the size and mass of nanoclusters will result in nanoparticle sedimentation, which will eliminate its effect on thermal conductivity. Keblinski et al. [172] also suggest that at high loading of nanoparticles, the effect of nanoclusters was promoted due to an increase in Van der Waals’s force of attraction among the nanoparticles.

The effect of the diffusive/ballistic nature of heat transport and thermophoresis has been reported [172]. Thermophoresis is related to thermal diffusion due to the temperature gradient. It describes the movement of the nanoparticles due to the temperature gradient from the high-temperature zone to
a lower-temperature zone which could influence the thermal conductivity. Thermophoresis is different from Brownian motion as the whole movement in thermophoresis is one-directional. The diffusive/ballistic nature of heat transport is an explanation for the heat transfer in crystalline solids. In solid media such as the nanoparticles used in nanofluids, the heat is transported by phonons. The thermal conductivity is significantly enhanced if a particle was influenced by a phonon that is created in another nearby particle that exists in the same liquid. This is because the mean free path of the phonon is shorter in the liquid than it is in the particles. However, the effect of Brownian motion, nanolayer and nanoclusters on thermal conductivity enhancement is more significant and the reasons mostly reported by the authors in 2019. These mechanisms have all been discussed in greater detail in review studies on heat transfer mechanisms in nanofluids [175–179].

Application of nanofluids in various thermal devices

Nanofluids in solar thermal collectors

Solar collectors are used in converting the radiant energy of the Sun to thermal or electrical energy, benefiting from radiative, convective and conductive heat transfer principles. The solar irradiance from the sun is absorbed by the collector with the aid of a working fluid flowing within its absorber. The common fluids used for thermal energy absorption are water, oils, ethylene glycol (EG) and salts. These working fluids have limitations that affect the overall efficiencies of various collectors. Their main limitation is in its low thermal conductivity. To obtain higher thermal conductivity, nanofluids have been proposed and tested for use in the various solar collectors. This section reviews the progress in the application of nanofluids in various solar collectors. Figure 4 presents a classification of different solar collectors that can use nanofluids as heat transfer fluids.

Flat plate collector (FPC)

The flat plate collector is the most widely used solar collectors. It is a rectangular tray consisting of an absorber surface (plate) with copper tubes (raiser) positioned along its surface. An insulating material placed at the backside helps reduce heat loss due to conduction, and a glass or transparent glazing over the top of the collector helps minimise radiative and convective heat losses. Figure 5 presents a schematic representation of the flat plate collector. To enhance
the efficiency of the collector, conventional fluids have been replaced with nanofluids. For instance, Choudhary et al. [180] investigated the stability of MgO nanofluids for use in a flat plate solar collector, considering the effect of volumetric concentrations between 0.08 and 0.4% on the stability of the nanofluid over time. The study demonstrated that the nanofluids achieved better stability at 0.04% volumetric concentration. Upon testing the nanofluids in the flat plate collector, the maximum thermal efficiency of 69.1% was achieved at a 0.2% volumetric concentration and 1.5 lit min\(^{-1}\). This value represents a 16.36% enhancement in thermal efficiency when compared to EG/water.

Ahmadlouydarab et al. [181] investigated the thermal absorption ability and the overall thermal efficiency of a flat plate collector using TiO\(_2\)–water nanofluids as an agent fluid in the outer part of the absorber of a flat plate collector. In this design, the nanofluids act as thermal insulation by utilising the high thermal capacity of these fluids. Furthermore, the TiO\(_2\) nanoparticle was used on the outer part of the glass cover of the collector to enhance the self-cleaning properties of the glass surface. The study concluded that the new system design enhanced the thermal efficiency of the collector by 49% at a 5% nanoparticle volumetric concentration.

Saffarian et al. [182] using Al\(_2\)O\(_3\) and CuO–water nanofluids investigated the effect of a change in the flow direction of the flat plate collector using modified U-shape, spiral and wavy pipes. The study demonstrates that the heat transfer coefficient increased by using nanofluids instead of water. The wavy and spiral geometries significantly improved the heat transfer; however, higher pressure losses were witnessed with the use of the wavy pipe. The study concluded that the use of the wavy pipes along with CuO nanofluids at 4% volume concentration increased the heat transfer coefficient by 78.25%.

Tong et al. [183] experimentally analysed the thermal performance of a flat plate collector using Al\(_2\)O\(_3\) and CuO nanofluids. It was demonstrated that with a 1% volume concentration of Al\(_2\)O\(_3\), the highest thermal efficiency enhancement of 21.9% was achieved. Furthermore, exergy efficiency enhancements of 56.9% and 49.6% were recorded when compared to water using Al\(_2\)O\(_3\) at 1 Vol% and CuO at 0.5 Vol%, respectively.

Mondragon et al. [184] tested the performance of a flat plate collector under laminar flow conditions using Al\(_2\)O\(_3\)–water nanofluids. The study demonstrated that at a 1% volume concentration of Al\(_2\)O\(_3\) in the nanofluids, a 2.3% increase in heat transfer coefficient could be theoretically attained. However, when testing for the collector efficiency, the study observed a decrease in the collector’s efficiency from 47% using water to 41.5% when using the Al\(_2\)O\(_3\)–water nanofluids. The decrease was attributed to the formation of nanoparticle deposition layers on the absorber tube; these layers acted as an additional form of resistance to heat transfer. The authors attributed the formation of these layers to the low flow velocity of the nanofluids.

**Evacuated tube solar collector (ETSC)**

This type of collector is more efficient than the flat plate collectors as heat losses in the ETSC are reduced when compared to the FPC due to the presence of vacuum insulation. A vacuum between the glass tube and the evacuated tube heat pipe helps to reduce losses due to convection and conduction. The heat pipe within the tube contains an antifreeze liquid in a closed system. This pipe then extends into the manifold where the liquid flowing in the manifold condenses the antifreeze and is then returned to be heated by the heat pipe. A pictorial depiction of this collector is shown in Fig. 6.

The use of nanofluids to enhance the performance of this collector has been investigated. For instance, Sarafraz et al. [185] evaluated the performance of an evacuated tube solar collector working with a carbon acetone mix in the heat pipe. The results demonstrate that the thermal efficiency of 91% was achieved, which is above that of the average thermal efficiency of 72.6% when using acetone alone.

Natividade et al. [186] experimentally evaluated an ETSC using multilayer graphene (MLG)-based water nanofluids. The ETSC was equipped with parabolic concentrators. The MLG at concentrations of 0.00045 Vol% and 0.00068 Vol% increased the thermal efficiency of the collector by 31% and 76%, respectively, when compared to the base fluid. Sadeghi et al. [187] also used a parabolic concentrator to enhance the performance of an ETSC operating with Cu\(_2\)O–water nanofluid. The experimental set-up was verified using an ANN multilayer perception model. The maximum thermal efficiency of 60% was attained at a flow rate of 50 litres/hour and 0.08 Vol% of Cu\(_2\)O. This value represented an 87.5% enhancement in the collector’s performance when compared to water.

![Fig. 6 Schematic diagram of an evacuated tube solar collector](image-url)
Compound parabolic collectors (CPC)

CPCs are similar to flat plate collectors but have parabolic optics attached to each tube, which concentrates incident solar radiation onto the absorbers. Similar to flat plate and evacuated tube collectors, CPCs can be static while collecting diffuse solar radiation. There are four kinds of CPCs: flat one-sided absorbers, flat two-sided absorbers, wedge-like absorbers and tubular absorbers as shown in Fig. 7. A tubular absorber contains a parabolic collector surface and an absorber tube. Korres et al. [188] investigated nanofluids-based CPC under laminar flow regime. The study demonstrated a mean and maximum heat transfer coefficient enhancement of 16.16% and 17.41%, respectively. Factoring in the effect of pressure losses as a result of using nanofluids, the study concluded that the pressure drops observed were not a limitation to the use of the nanofluids and recorded a thermal efficiency enhancement of 2.76% when using CuO/Syltherm nanofluids.

Linear Fresnel reflectors (LFR)

A linear Fresnel reflector is a concentrating solar collector characterised by its ease of assembly; this makes it cheaper when compared to other concentrating solar collectors. As shown in Fig. 8, the LFR utilises mirrors whose orientation revolves around a pivot following the Sun in order to concentrate its rays towards the absorber tube [189]. This system can produce thermal energy for medium- to high-temperature applications. However, LFRs are not as widely installed collectors; therefore, there are not as many studies applying the collector with nanofluids. Ghodbane et al. [190] performed a study to assess the performance of MWCNT–water nanofluid in the LFR. The outcomes indicate that MWCNT at 0.3 Vol% resulted in a more favourable thermal efficiency of 33.81% when compared to other fluids tested and resulted in the highest pressure loss of 2.3–46 Pa. The use of the nanofluids also demonstrated a reduction in the rate of entropy generation within the system.

Parabolic trough solar collectors (PTSC)

Parabolic trough solar collectors are the most commercially deployed and studied concentrating solar collectors available. As depicted in Fig. 9, the collector utilises a parabola-shaped mirror to reflect the solar radiation from the Sun onto a cylindrical receiver. The receiver comprises a concentric absorber tube enveloped with a glass cover. Solar radiation absorbed by the receiver is transferred to the working fluid passing through it, and it is then transported to applications requiring medium to high temperatures (50 °C–400 °C). Okonkwo et al. [191] synthesised zero-valent iron and TiO₂
nanoparticles from olive leaf extracts for use in a solar parabolic trough collector. The nanoparticles were used to prepare nanofluids with Syltherm-800 as base fluid. The use of Syltherm-800/TiO$_2$ and Syltherm-800/ZVI produced a 42.9% and 51.2% enhancement in the heat transfer coefficient at a 3% nanoparticle volume concentration. Although the use of the nanofluids resulted in an 11.5% drop in pressure, the authors stated that a thermal efficiency enhancement of 0.51% and 0.48% was still achieved while using Syltherm-800/ZVI and Syltherm-800/TiO$_2$ nanofluids, respectively. Ehyaei et al. [192] examined the energy, exergy and economic analysis of a PTSC operating with water and Therminol VP1 as working fluids. These fluids were also used as base fluid with the addition of CuO and Al$_2$O$_3$ nanoparticles. The annual efficiency of the PTSC was taken with all four working fluids, and the results indicate that the annual energy and exergy efficiency of water was 10.64% and 9.07%, while the addition of Al$_2$O$_3$ and CuO in water at 5% volume concentration only increased the efficiency of the PTSC by 0.03% and 0.09%, respectively.

Malekan et al. [193] investigated the heat transfer in a PTSC working with Fe$_3$O$_4$ and CuO/Therminol-66 nanofluids under an external magnetic field. The results demonstrated that by increasing the nanoparticle concentration, the heat transfer in the collector was enhanced. The maximum heat transfer enhancement observed in Fe$_3$O$_4$/Therminol-66 nanofluids was at 4% volume concentration and nanoparticle size of 10 nm. The presence of a magnetic field enhanced the performance of Fe$_3$O$_4$/Therminol-66 more than that of CuO/Therminol-66 nanofluid although the CuO nanoparticles had a better thermal conductivity.

Bellos and Tzivanidis [194] evaluated the performance of an LS-2 collector with six different nanoparticles (Cu, CuO, Fe$_2$O$_3$, TiO$_2$, Al$_2$O$_3$ and SiO$_2$) using Syltherm-800 as base fluid. The nanoparticle concentration was varied up to 6%, and their result showed that SiO$_2$ nanoparticle provided the least enhancement in thermal efficiency with 0.19%, while Cu with 0.54% provided the highest enhancement at a 4% volume concentration as shown in Fig. 10. Other nanoparticles CuO, Fe$_2$O$_3$, TiO$_2$ and Al$_2$O$_3$ had an enhancement of 0.46%, 0.41%, 0.35% and 0.25%, respectively.

**Direct absorption solar collector**

The direct absorption solar collector (DASC) is a concentrating solar collector with fewer thermal resistance when compared to regular solar collectors. By removing the absorbing surface, the working fluid can absorb solar radiation directly. As illustrated in Fig. 11, the conductive and convective resistance as a result of the use of a surface absorber is eliminated, making the efficiency of the system dependent on the absorptivity and thermal properties of the working fluid. This modification reduces the thermal losses in the system.

*Fig. 10* Thermal efficiency and overall heat transfer coefficient enhancement at 4 vol% [194]

*Fig. 11* Thermal resistance network for a regular solar collector, b direct absorption collectors
Qin et al. [195] stated that the direct absorption solar collectors are 5–10% more efficient than the regular parabolic trough collector. However, the challenge with these systems remains the low absorption properties of the working fluids. The use of nanoparticles dispersed in these working fluids can, however, improve the performance of the collector [30]. Tafarroj et al. [196] investigated the use of SiO$_2$/EG and MWCNT/EG nanofluids in a direct absorption solar collector. The outcomes suggest that at 0.6% volume concentration of nanoparticles, MWCNT/EG nanofluids provided the highest outlet temperature of 346.1 K. Simonetti et al. [197] performed a CFD study on direct volumetric absorption solar collector operating with SWCNT/EG nanofluids and compared its performance with a DASC integrated with a compound parabolic collector. The study concluded that the DASC performed better than the direct volumetric absorption solar collector.

**Photovoltaic thermal collectors (PVT)**

The cells of photovoltaic (PV) systems are affected negatively by high temperatures (>25 °C), as the excess heat received from the Sun reduces the efficiency of the PV module. Technologies such as the hybrid PVT system have been developed to extract this heat for possible utilisation in other thermal applications, while also enhancing the electrical output of the PV module. Evident from Fig. 12, the excess heat absorbed by the cells is transferred to a heat transfer fluid which cools the collector and provides heat for use in other thermal applications.

Sangeetha et al. [198] experimented to determine the performance of a hybrid PVT system utilising different nanoparticles dispersed in water. The study evaluated the performance of MWCNT, Al$_2$O$_3$ and CuO in water and demonstrated that nanofluids improved the electrical efficiency of the PVT when compared to water. The use of MWCNT and CuO nanofluids decreased cell temperature by 19%. MWCNT, Al$_2$O$_3$ and CuO nanofluids enhanced the electrical efficiency of the PV by 60%, 55% and 52%, respectively. Similarly, Alous et al. [199] investigated the performance of MWCNT and graphene nanoplatelets (GNPs) dispersed in water as coolant in a PVT system. The study concluded that the addition of the thermal module improved the exergetic efficiency of the system by 53.4% using water, 57.2% using MWCNT–water and 63.1% using GNP–water. An 18.6% enhancement in energy efficiency was recorded with the use of GNP–water nanofluids in the PVT collector. This represented the highest observed enhancement in energy efficiency in their study. Fudholi et al. [200], on the other hand, examined the use of TiO$_2$ water nanofluids on a PVT. The study concluded that at a mass concentration of 1%, the TiO$_2$ nanofluid recorded an 85–89% performance enhancement when compared to water with 60–76% at a mass flow rate of 0.0255 kg/s. Abdelrazik et al. [201] studied the effect of optical filtration along with nano-enhanced phase change materials (PCMs) on the performance of a PVT collector, demonstrating that optical filtration, and the use of nano-PCM, increased the overall efficiency of the collector by 6–12%. A combined PVT/PCM system using nanofluids has proved to be an effective coolant in enhancing the thermal conductivity of PVT collectors [202]. Other studies related to nanofluids in solar collectors investigated the photothermal properties of various mono and hybrid nanofluids [203–212], the impact of magnetic fields on the thermal performance of nanofluids in a solar collector [213], the forced convective behaviour of nanoparticles inside a solar collector [214] and more recently the application of ANN models for the prediction of nanofluids performance in solar collectors [215–217]. Other studies investigating the application of nanofluids in various solar collectors are presented in Table 7.

**Nanofluids in heat exchangers**

Heat exchangers (HX) are devices used for the transfer of heat between two or more fluids. The use of nanofluids in the different kinds of heat exchangers has been investigated and discussed below.
| References | Nanofluids used                  | Type of study | Type of collector | Efficiency enhancement | Key outcomes                                                                                                                                 |
|------------|---------------------------------|---------------|-------------------|------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| [218]      | WO₃/water                       | Experiments   | ETSC              | 23%                    | The enhancement from the use of nanofluids when compared to water was between the ratio of 1.05 and 1.16                                    |
| [219]      | Water–Al₂O₃, water–CuO and water–TiO₂ | Numerical      | ETSC              | 13.8% higher with CuO  | Recorded a 13.8%, 1.5% and 1.3% thermal efficiency enhancement for CuO–water, TiO₂–water and Al₂O₃–water, respectively                 |
| [220]      | Ag, ZnO and MgO in EG/water     | Numerical      | ETSC              | 26.7% for Ag/EG–water  | 30 solar collectors installed with using 4.0 Vol% Ag/EG–water nanofluids reduced coal, SO₂ and CO₂ emissions by 855.5 kg, 2241.4 kg and 7.2 kg per year |
| [221]      | CuO/water                       | Experimental   | ETSC              | 7.20%                  | Smaller particle size was more efficient in the collector                                                                                  |
| [222]      | Cu/water                        | Experimental   | ETSC              |                        | The absorbed energy parameter increases from 0.55 when using water to 0.65, 0.76 and 0.83 when using nanofluids at concentrations of 0.01%, 0.02%, and 0.03%, respectively |
| [223]      | Graphene–methanol nanofluids    | Experimental   | ETSC              | 35%                    | 95% enhancement in thermal efficiency was recorded                                                                                           |
| [224]      | Al₂O₃–water and CuO–water       | CFD            | ETSC              | 6.8% for CuO–water    | Both nanofluids improved the heat transfer while CuO–water nanofluid outperformed Al₂O₃ water                                                                 |
| [225]      | CuO/water                       | Numerical      | ETSC with parabolic concentrator | 10%                    | The energy and exergy efficiency of the system was enhanced 10% and 12.7%, respectively, at 0.08 volume fraction                          |
| [226]      | Syltherm/CuO                    | Numerical      | LFR               | 1%                     | The thermal efficiency enhancement at 4 mass % nanofluid with a finned absorber is 0.82%                                                       |
| [227]      | Al₂O₃–water                     | Experiment     | FPC               | 39.20%                 | Maximum energy and exergy efficiencies attained are 83.17% and 18.73% for nanofluids when compared to the maximum energy and exergy efficiencies obtained for water 59.72% and 12.29%, respectively, at a flow rate of 3 lpm |
| [228]      | TiO₂/WATER                      | Experiment     | FPC               | 22%                    | The heat transfer coefficient was improved by 22%                                                                                           |
| [229]      | Al₂O₃, TiO₂, ZnO, Al₂O₃ + TiO₂, TiO₂ +ZnO, ZnO + Al₂O₃ | CFD            | FPC               | 5.5% for nanofluids and 18% for hybrid | Maximum dynamic pressure in the nanofluid and hybrid nanofluid was about 48% and 16%, respectively                                                                 |
| [230]      | CeO₂/water                      | Experiments    | FPC               | 21.50%                 | Thermal efficiency enhancement of solar water heater with CeO₂/water nanofluid is 78.2%                                                    |
| [231]      | CNT/water                       | Experiments    | FPC               |                        | The maximum water temperature reached 75 °C with nanofluids and reached only 68 °C without nanoparticles.                             |
| References | Nanofluids used | Type of study | Type of collector | Efficiency enhancement | Key outcomes |
|------------|----------------|---------------|------------------|------------------------|--------------|
| [232]      | Al₂O₃, SiO₂ and CuO water | Numerical | FPC | 4.47%, 4.65% and 5.22% for Al₂O₃, SiO₂ and CuO | The nanofluids performed better than with 4.47%, 4.65% and 5.22% for Al₂O₃, SiO₂ and CuO nanofluids, respectively |
| [233]      | CuO + Al₂O₃/water, CuO/water and Al₂O₃/water | Experimental | FPC | 50% for CuO–water | The optimal enhancement of 50%, 16%, 15%, 8% and 2% for CuO, Al₂O₃, 25% CuO + 75% Al₂O₃, 75% CuO + 25% Al₂O₃ and 50% CuO + 50% Al₂O₃, respectively |
| [234]      | CeO₂/water | Experimental | FPC | 28.07% | The nanofluids saved 300.2 MJ of energy, led to a reduction of 175 kg in CO₂ and had a higher payback period of 2.12 years when compared to water |
| [235]      | CuO–water | Experimental | FPC | 55.1% | CuO–water enhanced energy efficiency by 15.2%, 17.1% and 55.1% for the flow rate of 1, 2 and 4 L/min, respectively |
| [236]      | MWCNT–water | Experimental | FPC | 35.20% | An enhancement in the exergy and energy efficiencies while using nanofluids when compared distilled water in both forced and thermosiphon systems |
| [237]      | Graphene nanoplatelet–water nanofluids | Experimental | FPC | 18.20% | The use of eco-friendly treated graphene nanoplatelets–water nanofluids showed enhanced performance |
| [238]      | Graphene nanoplatelets | Experimental | FPC | 13.30% | Yielded a 13.3% enhancement in thermal performance |
| [239]      | SiO₂/water | Experimental | FPC | 17.98% and 14.51%, for CuO and Al₂O₃, respectively | The removed energy parameter of nanofluids with volume concentrations of 0.4% and 0.6% reduces by 55.2% and 51.7%, respectively, relative to water |
| [240]      | CuO/water and Al₂O₃/water | Numerical | FPC | 17.98% and 14.51%, for CuO and Al₂O₃, respectively | The utilisation of the CuO nanofluid as the HTF is found to be more favourable for improving the performance of the cycle and decreasing the exergy-based cost of cooling |
| [241]      | Al₂O₃–Fe/water | Experimental | FPC | 2.16% in enhancement using Al₂O₃/water | 2.16% in enhancement using Al₂O₃/water and 1.79% decrease in efficiency while using hybrid nanofluids as compared to water |
| [242]      | CuO/water | Experiment | HPSC | 47.6% | Higher efficiency when using CuO nanofluid than pure water. The maximum efficiency attained was 88.6% at 0.017 Vol% |
| [243]      | Al₂O₃/water | Experiment | HPSWH | 55% | The highest thermal efficiency improvement of 19.34% occurred with nanofluid when compared to 12.46% using distilled water |
| [217]      | SiO₂/water | Numerical | PTSC | 13.30% | ANN is an effective tool in predicting the performance of PTC |
Table 7 (continued)

| References | Nanofluids used | Type of study | Type of collector | Efficiency enhancement | Key outcomes |
|------------|----------------|---------------|------------------|------------------------|--------------|
| [244]      | Fe₃O₄–SiO₂/water nanofluid | Experiment    | DASC             | 21.7%                  | The exergy efficiency enhancement is 66.4% |
| [245]      | Ferrofluids      | Experiment    | DAPTC            | 25%                    | Ferrofluids have good absorption and thermal properties even at low concentrations in the direct absorption solar collector |
| [246]      | TiO₂/water       | Numerical     | PTSC             | 0.27%                  | Entropy generation minimisation in a PTC using nanofluids |
| [247]      | Al₂O₃ and TiO₂/water | Numerical     | PTSC             | 34.51% for TiO₂/water  | Nanofluids as heat transfer fluid can result in increasing the efficiency of the collector |
| [248]      | Silver, aluminium, gold, nickel and titanium dioxide water | Numerical     | PTSC             | 1.09% using Al₂O₃-CeO₂/Syltherm-800 | An improvement in the critical heat flux occurs by adding various concentrations of the mentioned nanoparticles and is higher for Au–water and Al–water nanofluids |
| [249]      | Al₂O₃, CeO₂, CuO-Syltherm-800 | Numerical     | PTSC             | 1.09% using Al₂O₃-CeO₂/Syltherm-800 | The maximum thermal and exergy efficiencies enhancement using Al₂O₃-CeO₂/Syltherm-800 was 1.09% and 1.03%, respectively |
| [250]      | CuO–water        | Experimental  | PTSC             | 11%                    | Beyond 2.9 Vol%, the high viscosity obtained causes the efficiency of the collector to fall below that of water |
| [251]      | MWCNT/EG         | Numerical     | PTSC             | 8.60%                  | Improvement in solar efficiency increases with increasing particle concentrations, and the vacuum-insulated case has the highest efficiency |
| [252]      | Water + PEO + 1% CNT, PEO + 1% CNT and PEO + 0.2% CuO | Numerical     | PTSC             | 19.68% for (water + PEO + 1% CNT) | Enhancements while using nanofluids (water + PEO + 1% CNT, PEO + 1% CNT and PEO + 0.2% CuO) are (19.68%, 17.47% and 15.1%), respectively |
| [253]      | MWCNT–water      | Experiment    | PTSC             | 3%                     | The maximum charging efficiency of the system was 62% and 59% with MWCNT nanofluids and water, respectively |
| [254]      | CuO, ZnO, Al₂O₃, TiO₂, Cu, Al and SiC using water and Therminol VP1 | Experiment    | PTSC             | 15%                    | Maximum enhancements in heat transfer of 9.49% and 10.14% were achieved with Cu–water and Therminol VP1-SiC nanofluids during turbulent flow |
| [255]      | Al₂O₃–Therminol  | Numerical     | PTSC             | 15%                    | By using the rotating absorber tube along with nanoparticles, an increase of 15% in the thermal efficiency of the collector and a maximum decrease of 64 K in the absorber tube temperature are attainable |
| [256]      | Al₂O₃–Therminol  | CFD           | PTSC             | 15%                    | Thermal efficiencies enhancement was 14%, and energetic efficiencies were 15% for an inlet temperature of 600 K |
Double-tube heat exchanger

Double-tube heat exchange is a system widely used in industries. This type of heat exchanger consists of two concentric tubes, as illustrated in Fig. 13. Researchers have investigated various methods of improving the efficiency of these heat exchangers. Some of these include modifications in dimension, design of much larger systems and the use of a more powerful pump.

A novel method that has been recently promoted is the use of nanofluids [33]. Different nanofluids have been investigated for use in improving the performance of the double-tube heat exchanger. The performance of TiO$_2$–water nanofluid was experimentally investigated in a double-tube HX; the study observed that the heat transfer rate was improved by 14.8%; however, the pressure drop also increases by 51.9% [261]. The heat transfer coefficient in the double-tube HX was improved by 35% using MWCNT–water nanofluids [262]. The Al$_2$O$_3$/water nanofluid was also used in a double-tube HX, and the result demonstrated a more favourable thermal efficiency of 16% compared to pure water [263]. A study that investigated the heat transfer and pressure drop in the laminar flow regime using silver-coated silica demonstrated that the heat transfer coefficient could be improved from 7% to 50% [264]. The turbulent flow was also investigated for Al$_2$O$_3$/water nanofluid, and it was observed that the Nusselt number and Reynolds number increased by 23.2% and 32.23%, respectively [265].
Plate heat exchangers

The plate heat exchanger illustrated in Fig. 14 is a type of compact heat exchanger that is widely used in industries. The application of this type of heat exchanger has been recently spread in many industries. However, there is a need to improve thermal performance and efficiency; the use of nanofluids encourages a higher heat transfer rate within the same dimensions. Multiple studies investigate the use of nanofluids in plate heat exchangers [33]. The effects of using hybrid nanofluids on plate HX performance were numerically investigated [266], where heat transfer augmentation of approximately 16–27% was apparent for Al2O3–CuO/water nanofluid and Al2O3–TiO2/water nanofluid, respectively. Using an experiment conducted on a plate HX with Al2O3/water nanofluid, new correlations for Nusselt number and heat transfer enhancement rates were derived [267].

A study investigating the heat transfer enhancement when fly ash nanofluids are used as the working fluid concluded that the heat transfer rate was improved by 6–20% as the concentration increases. The maximum enhancement was achieved using nanoparticle mass concentration of 2% [268]. The effect of particle size of metal oxide nanofluids on plate HX was experimentally investigated: Al2O3–water with particle sizes of 20 and 40 nm, TiO2/water with a particle size of 10–25 nm and SiO2–water with a particle size of 20–30 nm. When SiO2–water nanofluid at a mass concentration of 0.2% was applied, the maximum heat transfer enhancement was achieved, while Al2O3–water nanofluid achieved the minimum heat transfer enhancement at a mass concentration of 0.1% [269]. The use of carbon-based nanofluids on brazed plate HX and its characteristic was investigated [270]. The results demonstrate a slight decrease in the pressure, while the heat exchange capacity and system efficiency factor were increased by 9.19% and 7.28%, respectively, at a mass concentration of 0.6%.

Shell and tube heat exchangers

The shell and tube heat exchanger is a type of heat exchanger that allows for larger surface contact when compared to other types of heat exchangers. It consists of a large outer tube which is the shell and bundles of inner tubes. Figure 15 illustrates a cross-sectional view of this type of heat exchanger. The rate of heat transfer with these heat exchangers is much higher due to their large contact area, although the low thermal conductivity of many of the heat transfer fluids used allows for the use of nanofluids with higher thermal conductivities. The heat transfer performance of carbon-based nanofluids on shell and tube HX was numerically investigated [271]. The study concluded that the nanofluid used improved the thermal performance; however, the pressure drop also increases as the particle volume concentration increased. The effects of using non-Newtonian metallic oxides nanofluids in the shell and tube HX energy-saving and effectiveness were experimentally investigated. Using Fe2O3, Al2O3 and CuO nanoparticles with water as the base fluid, the highest energy saving was achieved using CuO [272].

A study investigating the heat transfer characteristics of TiO2–EG nanofluids in a shell and tube HX determined that the heat transfer rate increases as the flow and volume concentration increases [273]. The study obtained the best volume concentration and flow rate for optimum heat transfer, where the best heat transfer rate achieved was 0.277 J at 0.075% nanoparticle concentration and a volumetric flow rate of 0.6 l/min. Said et al. [274] conducted an experimental and numerical study on the use of CuO/water as heat transfer fluid. The outcome demonstrates an increase in the heat transfer coefficient and convective coefficient by 7% and 11.39%, respectively. Moreover, a 6.81% reduction in the area could be achieved. The heat transfer improvement on the thermal performance of the shell and tube heat exchanger by the use of Al2O3/water and TiO2/water nanofluids was studied. The maximum heat transfer coefficient enhancement achieved by Al2O3/water was 41%, while the maximum heat transfer coefficient using TiO2/water was 37% [275].
| References | Nanofluid used                          | Method of study | Type of heat exchangers | Key outcomes                                                                                                                                 |
|------------|----------------------------------------|----------------|-------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| [276]      | TiO₂/deionised water and kaolin/deionised water | Experimental   | Plate heat exchangers   | The heat transfer rate using TiO₂/deionised water and kaolin/deionised water was 12% and 18%, respectively                                      |
| [277]      | MgO–oil based                          | Simulation     | Counter-flow double pipe | The heat transfer coefficient and heat transfer rate increased while the pumping power augments as well as the pressure drop increase           |
| [278]      | Al/water                               | Experimental   | Compact heat exchanger   | The average value of the Nusselt number was increased by 30.97 and 44.46% at concentrations of 0.1 and 0.2%                                |
| [279]      | TiO₂/Thermo Oil XT 32                 | Experimental   | Concentric tube         | Convective heat transfer coefficient of nanofluids TiO₂/Thermo XT 32 oil increases along with the increase in volume fraction                  |
| [280]      | TiO₂–water                             | Experimental   | Double-pipe counter-flow | The heat transfer coefficient of the nanofluids at a volume concentration of 0.5 Vol% was 15% higher than that of base fluid at given conditions. Also, the pressure drop slightly increased with the use of the nanofluids |
| [281]      | Al₂O₃/water                            | Simulation     | Double-pipe heat exchanger | Of the four shapes considered, the nanofluid containing spherical and platelet shape nanoparticles represent the maximum and minimum thermal and total entropy generation rates |
| [282]      | Al₂O₃, CuO and TiO₂ in water           | Simulation     | Pillow plate heat exchanger | The Al₂O₃-water with ϕ = 2% at all Reynolds numbers and the TiO₂-water with ϕ = 5% at higher Reynolds numbers have better performance among other nanofluids |
| [283]      | CNT, Al₂O₃ surfactant with deionised water | Experimental   | Plate heat exchanger     | They are beneficial for use in heat exchangers, where huge volumes of conventional fluids are needed                                          |
| [74]       | MWCNT/water                            | Experimental   | Helically coiled tube heat exchanger | Nusselt number is 28%, 52% and 68% higher than water and the pressure drop is found to be 16%, 30% and 42%, respectively, higher than water |
| [284]      | rGO–TiO₂                               | Theoretical    | A helically coiled heat exchanger | Percentage enhancement in the heat transfer coefficient was around 35.7%                                                                     |
| [285]      | Graphene-based and metal oxide nanofluids | Theoretical    | Heat exchangers          | The maximum enhancement in Nusselt number for GNP, GNP2, alumina and silicon dioxide nanofluids was achieved up to 84%, 72%, 26% and 28%      |
| [286]      | Zirconia nanofluids                    | Experimental   | Micro-heat exchanger     | Heat transfer coefficient and pressure drop were augmented by 40.1% and 67% at a mass concentration of 0.3% compared to the base fluid        |
| [287]      | Kaolin–deionised water                 | Experimental   | Plate heat exchanger     | An improvement rate in mean heat transfer coefficient was achieved as 9.3%                                                                |
| References | Nanofluid used | Method of study | Type of heat exchangers | Key outcomes |
|------------|----------------|----------------|-------------------------|--------------|
| [288]      | Aluminium and copper in ethylene–glycol and water | Experimental | Heat exchangers | The results suggest that nanopowders can substantially enhance wear by decreasing the anticorrosion action of ethylene glycol by a synergetic mechanism of erosion–corrosion |
| [289]      | SiC(P)/water, SiC(M)/water, SiC(P)/EG, and SiC(M)/EG | Experimental | Concentric tube heat exchanger | The experimental results show that the heat transfer coefficient rate of SiC(M) is higher than that of SiC(P) in both the case of water and the case of EG |
| [290]      | Water–Al₂O₃ and water–SiO₂ | Simulation | A spiral double-pipe | Water–Al₂O₃ and water–SiO₂ nanofluids are the best choices for the Reynolds numbers ranging from 10,551 to 17,220 and 17,220 to 31,910, respectively |
| [291]      | Boehmite alumina (γ-AlOOH) nanoparticles | Experimental | Horizontal double-pipe mini-channel | The nanofluids containing cylindrical and platelet-shaped nanoparticles have the highest thermal conductivity. Platelet shape demonstrates better heat transfer characteristics |
| [292]      | TiO₂/water | Simulation | Plate heat exchangers | TiO₂/water nanofluid improved the overall heat transfer coefficient averagely by 6%, whereas maximum improvement in overall heat transfer coefficient was 10% |
| [293]      | Al₂O₃–water | Experimental | A rectangular channel | At a mass concentration of 1% of nanofluid showed a maximum enhancement value of 54% in the transition flow regime and 11% in the turbulent regime |
| [294]      | Al₂O₃–MWCNT hybrid nanofluids | Experimental | Plate heat exchanger | Improvement up to 15.2% has been observed in the heat transfer coefficient for MWCNT (0:5) nanofluid with the negligible enhancement of 0.02% in the pump work and 2.96% enhancement in the performance index |
| [295]      | Al₂O₃–SiC, Al₂O₃–AlN, Al₂O₃–MgO, Al₂O₃–CuO and Al₂O₃–MWCNT | Experimental | Counter-flow plate heat exchanger | A maximum enhancement of around 31.2% has been observed in the heat transfer coefficient for Al₂O₃–MWCNT (4:1) hybrid nanofluid with the negligible enhancement of 0.08% in the pump work and 12.46% enhancement in the performance index |
| [296]      | Al₂O₃/water | Simulation and experimental | Double-tube heat exchangers | It was concluded that the Al₂O₃/water nanofluid’s thermal efficiency was 16% better than pure water |
| [297]      | Al₂O₃ in water | Simulation | Plate-type heat exchanger | An increase of 30% to 70% in the overall heat transfer coefficient is observed for an increase in nanofluid concentration. The determined hydraulic power (product of pressure drop and flow rate) exhibited a global minimum at 0.75% volume concentration of Al₂O₃ |
| [298]      | Al₂O₃ in water | Experimental | Concentric tube | Nanofluid volume concentration provided the most augmented heat transfer and enhanced the thermal properties |
| References | Nanofluid used | Method of study | Type of heat exchangers | Key outcomes |
|------------|----------------|----------------|-------------------------|--------------|
| [299]      | Al$_2$O$_3$/water | Experimental  | Double-pipe and plate heat exchanger | Heat transfer coefficient with a maximum enhancement of 26% for double-pipe HX, while only a 7% increment in the heat transfer coefficient is observed for the plate heat exchanger. Minimum pressure drop increase was 1% for the plate type |
| [300]      | Deionised water-based graphene | Experimental  | Helically coiled heat exchanger | Increase in heat transfer coefficient by 21–25% compared to that of the DI water |
| [301]      | CNT/Fe$_3$O$_4$ | Simulation   | Mini-channel hairpin | The increase in difference between the inlet temperatures of working fluids leads to the augmentation of heat transfer rate, overall heat transfer coefficient (except at Reynolds number of 500), heat exchanger effectiveness and PEC, while the pumping power diminishes with the increase in inlet water temperature |
| [302]      | CuO/(60:40) % ethylene glycol and water | Simulation   | Serpentine milli-channel heat exchanger | The pressure drop of nanofluids increases between 42% and 47% |
| [303]      | γ- Al$_2$O$_3$/water | Experimental  | Dimpled plate | The studies on pressure drop are also investigated to determine the friction factor of the fluid in the Reynolds number range |
| [304]      | Al$_2$O$_3$/Water | Experimental  | A double-pipe HX, a shell and tube HX and, a plate HX | Heat transfer coefficient with a maximum enhancement of 60% for double-pipe HX, while a maximum enhancement in the heat transfer coefficient of 11% was reported for the plate HX |
| [305]      | SWCNTs | Simulation & experimental | Microchannels heat exchanger | As the concentration of SWCNTs increases, the convective heat transfer coefficient and the pressure drop were intensified |
| [306]      | Al$_2$O$_3$–Cu/water | Simulation   | Single-pass shell and tube | The percentage increase in the heat transfer coefficient of hybrid nanofluid is 139% higher than water and 25% than Cu/water nanofluid |
| [307]      | Fe$_3$O$_4$/water | Simulation   | Double-pipe U-bend | The Nusselt number, for a 0.06% volume concentration of nanofluid, is enhanced up to 9.76% and 14.76% |
| [308]      | Al$_2$O$_3$/water | Experimental  | Rough plate heat exchanger | Increasing the volume fraction of nanoparticles and surface roughness enhances the heat transfer rate as well as increases the pressure drop in the plate heat exchanger |
Further studies related to the application of nanofluids in heat exchangers are presented in Table 8.

**Nanofluids in electronic cooling**

The advent of the miniaturisation of electronic devices and the need for effective heat management in such devices have pioneered new innovative research areas. The heat generated per unit volume of electronic devices has continued to increase, attributed to the flow of current through a resistance resulting in heat generation. The design of proper thermal management systems in such electronic devices is essential for the efficient and reliable operation of such devices. The use of microchannel heat exchangers in cooling electronic devices is one of the best options available. The channels are small, and as such, they increase the convective heat transfer from the electronic components. These types of heat sinks are used in the thermal management of devices such as supercomputers and batteries and are also used in data centres. The use of nanoparticles to enhance these microchannel heat exchangers has received much attention. The forced and natural convective heat transfer behaviours of nanofluids in various mediums have been studied. Such studies as the heat transfer behaviour of nanofluids in cavities [309–313], porous materials [314–316] and jet impinging [317] all show an increase in the dimensionless heat transfer parameter with the addition of nanoparticles. These studies prove the tremendous potentials of nanofluids in the electronics and data storage industries. Also, the heat transfer behaviour of nanofluids in magnetic fields has shown promising potentials [318].

Vishnuprasad et al. [319] experimentally evaluated the cooling performance of microwave-assisted acid-functionalised graphene (MAAFG) in water. The characterisation of the nanofluid showed that the MAAFG nanofluid had a 55.38% enhancement in thermal conductivity. The effect of varying the flow rate and nanoparticle volume concentration on the heat transfer coefficient and processor temperature was studied, and the results show that at 0.2 Vol%, there was an increase in the convective heat transfer coefficient by 78.5%. The processor temperature was also decreased by 15%, although a 5% pressure drop was recorded at 0.2 Vol% and a flow rate of 10 mL s⁻¹. Joy et al. [320] investigated the use of Cu–water and Al–water to increase the critical heat flux (CHF) limit in a heat pipe for electronic cooling. The result of the study demonstrated that nanofluids increased the CHF by 140% at a mass concentration of 0.01%. Both nanoparticle concentrations represented the optimum value of CHF for both nanofluids without preheating. Zing and Mahjoob [321] theoretically investigated the use of single- and multijet impingements through a porous channel for electronics cooling applications. The study evaluated the effect of two different coolants in their system: water and TiO₂–water nanofluids at a volume concentration of 5%. Results demonstrate that the use of TiO₂ nanofluid decreased the base temperature of the device more effectively than using water. For enhanced heat transfer in electronic cooling, Bezaatpour and Goharkhah [322] designed a mini heat sink with porous fins operating with a magnetite nanofluid of Fe₃O₄–water at volume concentrations up to 3%. The study recorded an increase in heat transfer of 32% with the use of the ferrofluids at 3 Vol% and Re of 1040. The pressure drop also recorded a decrease of 33% with the use of the ferrofluids.

Al-Rashed et al. [323] evaluated the first and second law performance of a non-Newtonian nanofluid of CuO and 0.5% carboxymethyl cellulose (CMC) in water for use in a microchannel heat sink (MCHS). Figure 16 illustrates an offset strip-fin MCHS with a description of its geometric parameters and imposed boundary conditions. By varying the nanoparticle concentration and Reynolds number, the effect of the nanofluids on the surface temperature of the CPU was observed. The results demonstrate that increasing Reynolds number adversely affected the frictional entropy generation and pressure drop. The nanofluid also reduced the surface temperature of the CPU and entropy generation rate in the system. A 2.7% decrease in the entropy generation rate of the CPU was attained at 1 Vol% and Re of 300. At 1

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**Fig. 16** The schematic of (a) offset strip-fin microchannels, and (b) the computational domain of the one unit of microchannels [323], [325]
Table 9  Studies related to the application of nanofluids in electronic cooling devices

| References | Nanofluid used | Type of study          | Cooling device used            | Key outcomes                                                                 |
|------------|----------------|------------------------|--------------------------------|-----------------------------------------------------------------------------|
| [326]      | Al₂O₃–water    | Experimental and analytical | Aluminium metallic foam        | Higher heat extraction was found at a nanofluid concentration of 0.2%       |
| [327]      | Al₂O₃–H₂O and CuO–H₂O | Experimental and analytical | Heat sink                      | The minimum base temperatures obtained for Al₂O₃–H₂O nanofluids and water were 43.4 °C and 45.2 °C, respectively, for the mini-channel heat sink with 0.5 mm fin spacing |
| [328]      | Ag–water       | Numerical               | Semicircular lid-driven cavity | Investigating the effects of the Richardson numbers of 1 and 10 and nanoparticle volume fractions on the flow field and heat transfer. The best heat transfer is related to Ri = 1 and φ = 6% for attack angles of −45°, 0°, −90°, 45° and 90° |
| [329]      | Graphene nanoplatelets | Numerical               | Pin fin heat sink               | Increase in the particle fraction and velocity reduces the temperature on the heating surface and improves the temperature distribution uniformity |
| [330]      | SiO₂–water     | Numerical               | Plate-pin heat sink            | Applying compact heat sink with nanofluids instead of the traditional heat sinks might produce a substantial enhancement in the hydrothermal performance of the heat sinks |
| [331]      | CuO–water      | Numerical               | Heat pipes                      | The use of nanofluid in the heat pipes resulted in a substantial decrease in the heat source temperature. For the application of nanofluids in heat pipes, the maturity of this technology has reached the Technology Readiness Level of 8 for surveillance systems tested |
| [5]        | Al₂O₃–water and TiO₂–water | Numerical               | Heat sink                       | It is found that nanofluids could enhance the microchannel heat sink performance as compared with that using pure water as the coolant due to the increase in thermal conductivity of coolant with the addition of nanoparticles |
| [332]      | Al₂O₃–water    | Numerical               | Plate fin heat sinks            | For the 1 vol% Al₂O₃–water nanofluid, when the Reynolds number increases from 500 to 1000, the pressure drop and frictional entropy generation of rectangular microchannel heat sink increase by 144% and 389%, respectively |
| [333]      | TiO₂–water     | Experimental            | Copper microchannel aluminium block | Thermal entropy generation decreases at higher TiO₂ nanofluid concentration and flow rate. The frictional entropy generation increases for higher flow rate and nanofluid particle concentration |
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Vol% and Re of 700, the CMC/CuO water had an optimal ratio of heat transfer to the pressure drop of 2.29. Qui et al. [324] investigated the interfacial transport between vertically aligned carbon nanotube and electronic heat sinks. Their results show that CNT reduced the thermal contact resistances from 10 mm²K/W to 0.3 mm²K/W. Other studies related to the use of nanofluid in improving heat transfer in electronic devices are detailed in Table 9.

Table 9 (continued)

| References | Nanofluid used | Type of study | Cooling device used | Key outcomes |
|------------|----------------|---------------|---------------------|--------------|
| [334]      | Graphene nanoplatelets–Ag/water | Numerical     | Heat sink           | Results showed that at an optimum percentage of dispersed nanosheets in water, the heat transfer behaviour of the coolant is enhanced |
| [335]      | Aluminium/water               | Numerical     | Heat sink           | With the nanofluids, the heat transfer decreases by 22% and total irreversibility decreases by 21% |
| [336]      | Al₂O₃–NH₃                     | Numerical     | Heat sink           | The ammonia base nanofluid (Al₂O₃–NH₃) outperformed other coolants (SiC–H₂O, TiO₂–H₂O, H₂O and Al₂O₃–H₂O) in pumping power demand with 0.144, 0.702, 0.724, 0.94 and 1.015 for Al₂O₃–NH₃, SiC–H₂O, TiO₂–H₂O, H₂O and Al₂O₃–H₂O, respectively |
| [337]      | Cu–water, Al–water            | Numerical     | Hemispherical cavity| The numerical approach shows that the average surface temperature of the electronic component decreases as the volume fraction increases, confirming the efficiency of the nanofluid in natural convective heat transfer improvement |
| [321]      | TiO₂–water, Al₂O₃–water, MWCNT–water, diamond in 40:60 EG/water | Numerical     | Porous filled heat exchanger | The use of titanium dioxide nanofluids (TiO₂) as a coolant for both copper and APG porous matrices at low and high porosity structures, and both square and rectangular inlet cross sections improve the cooling efficiency and temperature uniformity over the base |
| [338]      | Cu–water                     | Experimental  | Hemispherical cavity | The Cu–H₂O nanofluids degrade with its age and the number of times it has been used |
| [339]      | Ag–water                     | Numerical     | Microchannel heat sink | The addition of nanoparticles intensified the convective heat transfer coefficient leading to a decrease in the CPU temperature and thermal irreversibility rate and enhanced the CPU temperature uniformity |
| [340]      | SiC/EG–water                 | Numerical     | Wavy sinusoidal mini tube | Based on the performance evaluation criterion, the optimum tube using EG/water-based SiC nanofluid is 1.67 for a 4% volume fraction and nanoparticle diameter of 90 nm at Re= 15,000 |
Nanofluids in automobile radiators

The thermal management of automobile engines is necessary for the effective and efficient operation of the automobile. Figure 17 illustrates a schematic diagram of a car radiator which functions as a heat exchanger that disperses the heat generated from the operation of the engines. Recently, the use of nanofluids as alternative coolants in radiators have been investigated. Elsaid [341] experimentally investigated the performance of an engine radiator using nanofluids in the hot arid climate of Cairo, Egypt. Two nanoparticles Al₂O₃ and Co₃O₄ are used in varying concentrations in a base fluid of EG/water at 0:100%, 10:90% and 20:80%. A schematic of his experimental set-up for investigating nanofluids effectiveness in radiators is illustrated in Fig. 18. The study confirms that the use of Co₃O₄/EG–water results in a more favourable thermal performance than that of Al₂O₃/EG–water. The cobalt oxide also contributed to larger energy savings when compared to alumina. The nanoparticles enhanced the Nusselt number by 31.8%; however, this was at the expense of an increase of 16% in friction factor. This reduction in friction factor resulted in the need for additional pump power for the nanofluids. It is essential to note that pump power was also intensified with the use of EG–water as the base fluid.

Fig. 17  Schematic diagram of a car radiator

Fig. 18  Schematic diagram of the experimentation system used by Elsaid [341]
performance of a hybrid of Al$_2$O$_3$ nanocellulose dispersed in EG/water in a radiator was investigated by Naiman et al. [342], who recorded a maximum thermal conductivity at 0.9 Vol% and concluded that the nanofluids were more efficient than the use of EG–water. Al Rafi et al. [343] studied the heat transfer potential of Al$_2$O$_3$/EG–water and CuO/EG–water in a car radiator, revealing that the addition of EG into the water decreased the overall heat conductance by 20–25%. Moreover, experimental results demonstrate that Al$_2$O$_3$/EG–water at 0.1 Vol% and CuO/EG–water at 0.2 Vol% improved the heat transfer potential of the radiator by 30–35% and 40–45%, respectively.

Kumar and Sahoo [344] analysed the energy and exergy performance of a wavy fin radiator using Al$_2$O$_3$–water nanofluid as a coolant. The effect of various nanoparticle shapes (spherical, brick and platelet) on the radiator’s effectiveness, pump power and heat transfer was also investigated; results show that the shape of the nanoparticles affected their performance in the radiator. Furthermore, it was observed that the spherical nanofluids had a 21.98% enhancement in heat transfer when compared to the platelet nanofluid. A 13% enhancement in the exergy efficiency of the spherical nanofluids determined that the use of spherical nanofluids performed better in comparison with nanofluids of other shapes. Contreras et al. [345] experimentally investigated the thermo-hydraulic performance of silver/EG–water and graphene/EG–water for use in a radiator. The study showed that silver/EG–water had an improved heat transfer rate of 4.7% when compared to EG–water, while the heat transfer using graphene nanofluid decreased by 11% and 3% at concentrations for 0.01 Vol% and 0.05 Vol%, respectively, when compared to water. The thermo-hydraulic performance coefficient of all nanofluids showed that nanographene at 0.1 Vol% and silver nanofluids at 0.05 Vol% had values of 1.5% and 2.5%, respectively, while graphene nanofluids at concentrations of 0.01 Vol% and 0.05 Vol% were not suitable for use in the radiator as they performed below EG–water. Other studies on the use of nanofluid in improving the performance of automobile radiators are detailed in Table 10.

**Nanofluids in thermal storage**

Thermal energy storage (TES) is a very important part of the utilisation, conservation and development of new and existing energy sources. The three forms of TES are chemical energy storage, sensible heat storage and latent heat storage. The difference between sensible and latent heat storage types is related to the phase transition of the thermal material used for storage. There is a phase transition before energy is released or stored in the Latent TES, while sensible TES does not require a phase change and operates mainly with the changing temperature of the material. Phase change materials (PCMs) can be used in both cases and is essential to the operation of the latent TES unit. The drawbacks of PCMs are their low thermal properties.

A classification of the various materials used in thermal energy storage is presented in Fig. 19. Highlighting the studies that investigate the effects of nanoparticles on the thermal performance of PCM, Bondareva et al. [357] investigated the heat transfer performance of the nano-enhanced phase change material system under the inclination influence. Studying the performance of paraffin enhanced with Al$_2$O$_3$ nanoparticles, they discovered that, for small inclinations of the cavity, when convective heat transfer dominates, an increase in the nanoparticles volume fraction leads to an increase in the melting time. Navarrete et al. [358] proposed the use of molten salt-based nanofluid for both sensible and latent energy storage. The molten salt nitrate would serve as the base fluid for the nano-encapsulated phase change materials (nePCM) consisting of Al-Cu alloy nuclei. Oxidation that occurs as a result of the metals been exposed to air would serve as an encapsulation over the nanoparticles. The study tested the resistance of the oxide shell to temperatures up to 570 °C, demonstrating that although the specific heat and by extension the sensible heat storage decreased with the presence of solid content, the phase change enthalpy and latent storage capacity increased by 17.8% at constant volume bases. Furthermore, the thermal conductivity of the salt nitrates increased with the addition of nanoparticles enhancing the heat transfer performance of the PCM nanofluid. Martin et al. [359] developed a novel nePCM from two fatty acids of capric acid (CA) and capric–myristic (CA–MA) using nSiO$_2$ for thermal energy management in a building. The addition of the 1.5% nSiO$_2$ significantly improved both the thermal conductivity and specific heat of nePCM. The thermal stability tests after 2000 thermal cycles indicated that the addition of nanoparticles did not affect the thermal stability of CA, but slightly improved that of CA–MA. The sensible heat storage capacity of both fatty acids improved due to a 20% improvement in specific heat capacity at a volume concentration of 1%; however, the latent energy storage capacity of both fatty acids was lowered. The use of the nSiO$_2$ nanoparticles strengthens on the initial weaknesses of the fatty acids as heat storage fluids as Fig. 20 illustrates.

Ding et al. [360] studied the use of two crystal forms of TiO$_2$ nanoparticles (anatase referred to as A and rutile referred to as R) dispersed in water operating in a microchannel inside a PCM used to enhance the thermal storage in miniaturized devices. The two nanofluids R-TiO$_2$–water and A-TiO$_2$–water were thermally tested, and both nanofluids confirmed to be stable. R-TiO$_2$–water was more stable than A-TiO$_2$, and the thermal conductivity of R-TiO$_2$ was found to be higher than that of A-TiO$_2$. The addition of TiO$_2$–water in the microchannel at a volume concentration of 0.5%, 0.7% and 1.0% decreased the complete melting time of paraffin by 7.78%, 16.51% and 32.90% while increasing the complete
Table 10  Studies related to the application of nanofluids in automobile radiators

| References | Nanofluid used | Type of study | Enhancement observed | Key outcomes |
|------------|----------------|---------------|----------------------|--------------|
| [346]      | Al$_2$O$_3$ and TiO$_2$ in water/EG | Experimental | 24.21% for Al$_2$O$_3$-water | The use of Al$_2$O$_3$ nanoparticle provided the most enhancement in the Nusselt number. An enhancement of 9.79% at 0.05% concentration and 24.21% at 0.3% concentration at a mass flow rate of 1 L min$^{-1}$. |
| [347]      | Cu–water       | Experimental  | 39.50%               | Nanofluids enhance the heat transfer coefficients by 19.187%, 23.425% and 26.465% for 0.3%, 0.6% and 1.0% volumetric concentration, respectively, when compared to water. |
| [348]      | TiO$_2$, TiO$_2$ doped with 0.1% Ag, TiO$_2$ doped with 0.3% Ag, TiO$_2$ doped with 0.1% Cu in EG/water | Experimental and theoretical | 27.9% for Al$_2$O$_3$ doped TiO$_2$ at 0.4% vol% | The convection heat transfer coefficient and overall heat transfer coefficient for the 0.3% Ag-doped nanofluids with concentrations of 1% and 2% increased when compared to water/EG mixture under constant thermal power and constant flow rate conditions. An increase of 11.094% was recorded using 0.3% Ag. |
| [349]      | Al$_2$O$_3$/MgO, Al$_2$O$_3$/TiO$_2$ in EG/water | Experimental | 27.9% for Al$_2$O$_3$/TiO$_2$ at 0.4% vol% | A 27.9%, 25.24% and 33.18% increase in the heat transfer rate was achieved using Al$_2$O$_3$/TiO$_2$ at 0.4 Vol%, 0.12% Mg–Al$_2$O$_4$ and 0.4% Mg–Al$_2$O$_4$ when compared with water. |
| [350]      | Fly ash/EG–water | Experimental | 27.9% for Al$_2$O$_3$/TiO$_2$ at 0.4% vol% | A 2% volume concentration of fly ash in 40:60 EG/water coolant can improve the overall performance of heavy vehicle radiators. |
| [351]      | MWCNT–water    | Experimental  | 45%                   | Functionalised MWCNT nanofluid exhibited an improved greatly the rate of heat transfer compared to the DI water. Due to its superior thermal conductivity (0.92 w/m 2 k at 80 C). |
| [352]      | Water-based graphene nanoplatelets | Numerical | 74.18% enhancement in Nusselt number at 0.5 vol% for the case of Reynolds number of 2000. They concluded that this enhancement could improve the performance of the automotive cooling system, leading to a reduction in radiator size and reducing the fuel consumption in the automotive engine. |
| [353]      | CuO/EG–water   | Experimental and theoretical | 20%                   | 20% enhancement is observed for ethylene glycol–water (40:60) mixture at 1 Vol% of CuO. As the heat transfer rate increases with the use of nanofluids, the heat transfer area of the radiator can be minimised. |
| [354]      | ZnO–PG, α-Al$_2$O$_3$–PG and γ-Al$_2$O$_3$–PG | Experimental | 40% with MWCNT–water | The volume concentration influences the transfer coefficients of the nanofluids. Smaller particles provided a better cooling performance, and the 0.1 Vol% γ-Al2O3–propylene glycol nanofluid had a 19.9% increase in heat transfer coefficient compared with that of α-Al2O3–propylene glycol. An increase in flow rate resulted in a 10.5% increase in the heat transfer coefficient of the 0.5 Vol% α-Al2O3–propylene glycol nanofluid. |
| [355]      | Cu, Al$_2$O$_3$, MWCNT–water | Experimental | 40% with MWCNT–water | The maximum enhancement in the overall heat transfer coefficient was observed to be 40%, 29% and 25% for MWCNT, copper and aluminium nanofluids, respectively. |
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...solidification time by 7.42%, 15.65% and 22.57% in the solidification process. The use of nanofluids increased the melting and solidification pressure by less than 8% in both cases. Harikrishnan et al. [36] investigated the effect of Ni–ZnO nanocomposite dispersed in oleyl acid on the thermal conductivity and phase change properties of the resulting nePCM. The thermal reliability along with the freezing and melting characteristics of the nePCM was studied, and the thermal conductivity of the nanofluids was confirmed to be higher than that of oleyl acid. For the mass fraction considered, 0.3, 0.6, 0.9 and 1.2% of Ni–ZnO, the complete melting and solidification processes were enhanced by 7.03%, 14.06% 24.21%, 29.69% and 7.58%, 13%, 19.13%, 28.52%, respectively. The trend confirms that the time required in melting and freezing was lowered with the use of the nano-PCMs. Other studies related to the use of nanoparticles in thermal storage units are detailed in Table 11.

**Nanofluids in refrigeration**

Nanofluids can also be used in air conditioning and refrigeration systems. The negative environmental effect of using chlorofluorocarbons along with hydrofluorocarbons has propelled research into alternative refrigerants. Traditionally, vapour compression refrigeration systems (VCRSs) are used in the cooling industry; however, the major drawback to this system is the large compressor power requirement. An alternative heat-powered absorption refrigeration system (VARS) has been developed, although the coefficient of performance (COP) of these systems is still below those of the VCRS. Nanoparticles have been used to create new refrigerants known as nanorefrigerants which can improve the COP of both the VARS and VCRS and decrease the compression work of the VCRS.

Rahman et al. [376] analysed the effect of using nanoparticles in a refrigerant. The effect of the nanorefrigerant on the compression work and COP of the air conditioning system is observed. They observed that the addition of 5% SWCNT to R407c refrigerant at temperatures between 283 K and 308 K resulted in a reduction in the energy consumption of the compressor by 4%. Moreover, the nanorefrigerant had improved the thermal conductivity and specific heat values by 17.02% and 10.06%, respectively. The nanorefrigerant also enhanced the COP by 4.59% and reduced the compressor work by 34% when compared to conventional vapour compression refrigeration systems.

Jiang et al. [377] investigated the effect of 0.5% TiO₂ and 0.02% SDBS on the COP of ammonia absorption refrigeration system (AARS). The experimental set-up of the test rig used in their investigations is illustrated in Fig. 21. Outcomes of the experiment were compared to that of 0.1%, 0.3% and 0.5% of TiO₂ dispersed in ammonia water as a refrigerant. The results demonstrate that the
addition of TiO$_2$ to any of the concentrations studied significantly improved the COP of the AARS. It was observed that the further addition of 0.02% of SDBS improved the stability of the mixture and enhanced the COP by 27% as shown in Fig. 22. In conclusion, the improvement in COP of the AARS was strongly dependent not only on nanoparticle concentration but also on the number of nanoparticles stably dispersed in the base fluid. Jeyakumar et al. [378] investigated the use of three nanoparticles CuO, ZnO and Al$_2$O$_3$ in the refrigerant of a vapour compression system. The nanoparticles were added to refrigerant R134 at concentrations of 0.06%, 0.08% and 0.1% with 0.1% polyester oil as a lubricant. The results demonstrate an improvement in COP of 12.2% and 3.42% using the nanorefrigerant of CuO and Al$_2$O$_3$, respectively, was observed. Other studies related to the use of nanoparticles in compression and absorption refrigeration systems are given in Table 12.

The use of nanofluids in many other devices has also been studied, and some of these include the application of nanofluids in solar still [389, 390] and also in mineral oil to enhance the insulating properties of high-voltage AC and DC transformers as proposed by Rafiq et al. [391].

**Challenges and future prospects**

Due to stability concerns with nanofluids, exponential improvements are required for nanofluids to reach their full potential as heat transfer fluids. The problems with stability are more obvious in liquids with low viscosity than...
| References | Nanofluid used | Type of study | Enhancement observed | Key outcomes |
|------------|---------------|---------------|----------------------|--------------|
| [363]      | R1234Ze/UiO-66 | Molecular simulations | Thermal heat storage | Adding UIO-66 particles in organic R1234ze can enhance the thermal energy storage density of R1234ze, and the thermal energy storage density increases as the UIO-66 mass fraction rises |
| [364]      | UIO-66/H₂O nanofluids | Experiment and theoretical | Thermal heat storage | The results of both methods suggest that the thermal energy storage capacity of UIO-66/H₂O nanofluids is enhanced with the increase in the mass fraction of UIO-66 |
| [365]      | Al₂O₃-water | Experimental | Thermal heat storage | The percentage of reduction in charging time of about 22% was achieved for high nanoparticle concentration. Also, an enhancement in charging time by increasing the refrigerant flow rate reached 38% when the mass flux varied from 200 to 400 kg/m²s |
| [366]      | SiO₂–NaNO₃ and KNO₃ | Experimental and molecular dynamics simulation | Thermal heat storage | Average enhancements of specific heat capacity using 10, 20 and 30 nm nanoparticles in the liquid phase were found to be 8.4%, 26.7% and 19.4%, respectively |
| [367]      | CuO–n-octadecane paraffin | Numerical | Thermal heat storage | The heat transfer rate is higher at lower fins due to the strong aiding effects of buoyancy force resulting from the use of nanoparticles |
| [368]      | CuO/paraffin | Experiment | Thermal heat storage | The nano-PCM enhances the solar thermal conversion capacity by enhancing the light absorption ability of PCMs |
| [369]      | CuO/paraffin | Experiment | Thermal heat storage | The melting and solidification show that the latent thermal storage is enhanced with nanoparticles when compared to the base material |
| [370]      | Al₂O₃ and SiO₂–NaNO₃/KNO₃ | Experiment | Thermal heat storage | Nanoparticle doping complex effects on the corrosion rates of carbon steel. In particular, if the negative effect of microbubbles of air trapped between the nanoparticles is not predominant, one can obtain reduced corrosion rates due to the incorporation of the nanoparticles into the oxidation layer |
| [371]      | Al₂O₃/Paraffin | Numerical | Latent thermal energy storage | An increase in the nanoparticles volume fraction improves the melting rate |
liquids with high viscosity. Most of the current methods used to increase fluid stability appear to fall short in certain regards. pH modulation has demonstrated promising signs of improving the stability of nanofluids; however, acidic and basic solutions exponentially increase corrosion in metals and would thus render heat transfer system untenable. The addition of surfactants has the potential to improve nanofluids stability, however, at high-temperature surfactants tend to foam and decrease the overall efficiency of the system. The most promising technique for increasing fluid stability is by improving the synthesis techniques used. Incidentally, the most common method for synthesising nanofluid is the worst performing method for ensuring fluid stability. Green synthesis techniques demonstrate sufficient promise in improving stability; however, the thermal performance of the green-synthesised nanofluids is not normally as high as nanofluids synthesised by the two-step technique. Furthermore, there appears no standard for reporting the stability of nanofluids. Therefore, a generic standard for measuring nanofluid stability must be developed so that easy comparisons can be made across nanofluid types.

Another significant challenge is the theoretical unpredictability of the thermophysical behaviour of nanofluids. While
Table 12  Studies related to the application of nanofluids refrigeration systems

| References | Nanofluid used | Type of study | Enhancement observed                                                                                                                                                                                                                                                                                                                                 | Key outcomes                                                                                                                                                                                                                           |
|------------|----------------|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [379]      | Al₂O₃, TiO₂, and a hybrid of Al₂O₃/TiO₂ water | Experiment vapour compression refrigeration | Al₂O₃/water contributed a higher coefficient of performance and a lower elapsed time for cooling the fluid of a chiller system. Higher values of the VCRS COP were obtained at lower values of air velocity of air conditioner and higher values of the nanofluid flow rate of the chiller unit. The Al₂O₃/H₂O provided lower values of compression ratio and higher values of the refrigeration effect in comparison with TiO₂/water by approximately 4.1% and 5.3%, respectively   |                                                                                                                                                                                                                                         |
| [380]      | Fe₃O₄/LiBr water | Experiment Solar absorption refrigeration | The photothermal characteristics of the nanofluids for absorption refrigeration were studied. An increase in bulk temperature and surface evaporation rate of iron oxide-based nanofluids under solar simulator shows their efficient photo-to-thermal energy conversion and the consequently enhanced vaporising ability. Both the sensible and latent heat capture were boosted for nanofluid                                                                 |                                                                                                                                                                                                                                         |
| [381]      | MWCNT-CuO(30–70%)/SAE50 | Experiment Refrigeration systems | It was found that, in high volume fractions (e.g., 1%), the viscosity increased by 10%, which is small compared to the reported amounts for an increase in the viscosity of other nanofluids                                                                                                                                                                                                 |                                                                                                                                                                                                                                         |
| [382]      | Cu/water–EG | Numerical Barocaloric regenerative refrigeration cycle | The results reveal that, as a general trend, the effect of adding 10% Cu nanoparticles in the water/ethylene–glycol mixture enhances heat transfer by as much as 30%                                                                                                                                                                                                       |                                                                                                                                                                                                                                         |
| [383]      | Antifreeze-CoFe₂O₄/SiO₂ | Experiment Refrigeration condensers | The nanofluids cause changes by the increase in the temperature (15–65 °C) in most cases for the mass fraction increase by 37.7%                                                                                                                                                                                                                       |                                                                                                                                                                                                                                         |
| [384]      | Graphene–acetone/ZnBr₂ | Experiment Absorption refrigeration | A small proportion of nanoparticles can offer benefits by improved boiling at lower temperatures where the temperature potential above saturation reduces                                                                                                                                                                                                                  |                                                                                                                                                                                                                                         |
| [385]      | Ag–water, Al–water and Al₂O₃–water | Numerical Absorption chiller | The use of Ag–water was found to improve the system’s efficiency from 77.3% to 81%                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                         |
| [96]       | Acetone/ZnBr₂-ZnO | Experiment Absorption refrigeration system | The results indicate that converting the acetone/ZnBr₂ to a nanofluid provides a potential improvement on the performance of this fluid in the vapour absorption refrigeration system                                                                                                                                                                                                 |                                                                                                                                                                                                                                         |
| [386]      | Al₂O₃-POE oil | Experiment Vapour compression refrigeration | Using 0.1% Al2O3 nanoparticle concentration, the COP of the system was improved by 17.27%, and energy consumption was reduced by 32.48%.                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                         |
many studies settle for regression-based correlation models to predict thermophysical properties, intelligent computing has also been widely used in the predictions. It is the opinion of the authors that because of the almost infinite variables that affect the thermophysical behaviour of nanofluids, intelligent computing would be the most accurate predicting the thermophysical behaviour of nanofluids. Therefore, a generic standard must be developed for labelling data obtained from the experiments measuring thermophysical properties of nanofluids. Developing a global data bank will drastically improve the prediction accuracy of artificial neural network and machine learning models, saving unlimited research costs in conducting thermophysical behaviour measurements.

To improve numerical analysis models, further nanofluid heat transfer correlation studies are required for determining the Nusselt number correction equation. Many studies adopt the Nusselt number correlation equation proposed by Pak and Cho [392]; however, this model was developed for water, Al₂O₃–water and TiO₂–water nanofluids and may not be particularly accurate for other nanofluids. More experiments using other nanofluids, especially for hybrid nanofluids, will further enlighten the field and improve the accuracy of numerical studies.

Finally, the classification of nanofluids must be improved. As nanofluid research increases, several unique types of fluids are synthesised. Previously, conventional fluid often implies fluids with a single-particle material, while hybrid nanofluid refers to a fluid with more than one nanoparticle material. However, it appears that further classifications are required as nanofluid have the potential to have an nth number of significant nanomaterials types present in the fluid. Some authors have sought to classify nanofluids with two significant nanomaterials type as “binary hybrid nanofluid” and nanofluids with three significant nanomaterials type as “ternary hybrid nanofluid”. It may be beneficial if classifications are conducted along these lines.

### Conclusions and recommendations

The use of nanofluids as coolants in heat transfer devices has gained attention over the years. This study presents a detailed review of studies relating to the preparation, thermophysical property measurements and application of nanofluids in a range of thermal devices requiring efficient heat transfer published in 2019. Some of the areas reviewed include thermophysical models used in determining the properties of the nanofluids, mechanisms that support the enhanced thermal behaviours of nanofluids, and the application of different nanofluids in devices such as solar collectors, heat exchangers, electronics cooling and thermal storage. Based on the articles reviewed in this study, the following recommendations are made:

#### On the preparation of nanofluids:
- Few studies on the preparation of nanofluids based on the one-step method are available, and this method has been proven to have better stability than the two-step method. More studies on the production of nanofluids using the one-step method are needed, as this could help in the development of more cost-effective means for the large-scale production of nanofluids.

#### Regarding the thermophysical properties of nanofluids:
- An increase in the nanoparticle volume concentration leads to a decrease in the specific heat capacity of nanofluids in cases where the heat capacity of base fluids is higher than those of nanoparticles. Since a higher heat capacity is needed in coolants, further studies are required to assess how this phenomenon can be improved.
- Many studies on the thermal behaviour of nanofluids were conducted for temperatures between 10 and 100 °C. The interaction mechanism of nanoparticles in base fluids for heat transfer at higher temperatures (greater than 100 °C) and cryogenic conditions requires further investigation.
• There exist huge differences between the heat transfer predicted by the single-phase homogenous model and those obtained from experiments. More studies related to the development of other models (two-phase models) are required which allude to defining the conditions where the single-phase models can be applied to provide more accurate results.

• There has been an increase in both the number and methods for developing correlation models that predict the thermophysical properties of nanofluids. However, more correlation equations that predict the heat transfer (Nusselt number) and friction factor behaviours of many nanofluids are needed.

On studying the mechanisms that influenced the properties of nanofluids:

• Knowledge of the dominant forces responsible for the behaviour of nanorefrigerants in various flow configurations requires further development.

• An understanding of the impact of nanoparticle morphology (size and shape), nanoparticle mixture ratio (for hybrid nanofluids) on heat transfer augmentation is limited. More studies are needed to understand the impact of these on the performance of nanofluids in heat transfer devices.

Investigation on the various heat transfer devices:

• Further studies are required, as there are contrasting reports on the effect of nanoparticle loading on the pressure drop and additional pump power requirement. While some studies claim that the effect of particle loading increases the pressure drop and consequently the pump power requirement of the system, others argue that when the heat transfer rate obtained using nanofluids is compared with that of conventional fluids, the nanofluids lowers the pump power requirements.

• In heat exchangers and car radiators, the constant rate of heat transfer from the use of nanofluids leads to a reduction in the heat transfer surface. This can result in an improvement in the size and volume of these devices. Such improvements would lead to a reduction in the drag forces witnessed in vehicles and increase the performance of the engine.

• The most common model used in the literature for the simulation of nanofluids remains the finite volume method. Further studies using other methods are needed for the comparison of the different numerical approaches.

• Further studies on the effects of erosion of heat transfer and corrosion of flow channels resulting from the use of nanofluids, especially in high temperatures, are required. Both the short- and long-term impacts of sedimentation and nanoparticle deposition on the efficiency of heat transfer devices require investigation.

• Few studies are available on the production cost and environmental impact of nanofluids. Such factors present huge hurdles to the commercialisation of nanofluids.

• Further information on the effect of oxidisation of metallic nanoparticles used with phase change materials on the thermal performance of the thermal storage unit is required, especially during the melting phase.

Acknowledgements Open Access funding provided by the Qatar National Library.

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