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REVIEW PAPER

Factors affecting nanofluids behaviour: A review

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ABSTRACT

Nanotechnology applications have occupied a wide range in engineering applications and achieved distinctive performance due to their potential as a working fluid instead of conventional liquids due to their outstanding performance. Sustaining stable performance nanofluids for a longer time retaining their properties without clustering and nanoparticles aggregation in the base fluid represents a significant challenge that can influence nanofluid properties and thermal behaviour. This review highlights some important factors that influence the stability of nanofluids, such as the size, concentration ratio of nanoparticles, and the type of base fluid, in addition discussing the methods used to improve the stability of nanofluids, such as the effect of cluster formation of nanoparticles in the base fluid due to Brownian motion and the role of the surfactants in preventing or reducing the agglomeration of nanoparticles, zeta potential and pH in estimating nanofluids stability. The factors mentioned affect the thermophysical properties of nanoparticles in preparing nanofluids and enhance their performance. This review provides information which helps improve the wide range usability of nanofluids for preparing stable nanofluids with good thermophysical properties.

KEYWORDS

nanoparticles, stability of nanofluids, sedimentation of nanoparticles, surfactants, thermophysical properties, base fluid

1. INTRODUCTION

Conventional liquids such as water and any equivalents are characterised by low thermal properties, which impede the thermal systems efficiency and other thermal applications that adopt the water and equivalents in their application [1]. Different methods have been used to enhance the thermal properties of conventional fluids. Nanofluids are a mixture of small-sized solid particles of less than 100 nm with base fluids (water, kerosene, oil, etc.) to produce a nanofluid with better heat transfer properties than the base fluid [2]. Recently, the use of nanofluids has occupied a wide range in heat transfer applications. Figure 1 shows the number of publications on nanofluids used in different applications, such as heat exchangers, solar energy applications, diesel-ethanol used in engines, thermal storage systems, radiator cooling applications, biodiesel fuel, etc. [3–8]. In heat transfer and energy storage applications, nanofluids have better characteristics than other fluids, such as specific heat, thermal conductivity and other unique mechanical, electrical, magnetic, and optical properties [9]. The nanofluids have good properties such as high thermal conductivity and low viscosity with high photo-thermal properties that are attractive for thermal applications [10, 11].

The nanoparticles have more stability when dispersed into fluids; this leads to enhanced fluid thermal advantage. Nanofluids have a thermal advantage but suffer from some problems in thermal applications, such as sedimentation and aggregation of nanoparticles into the fluid, despite using ultrasonication and adding surfactants [12]. Other parameters could affect nanofluids stability periods, such as the type of nanoparticles, base fluid used,

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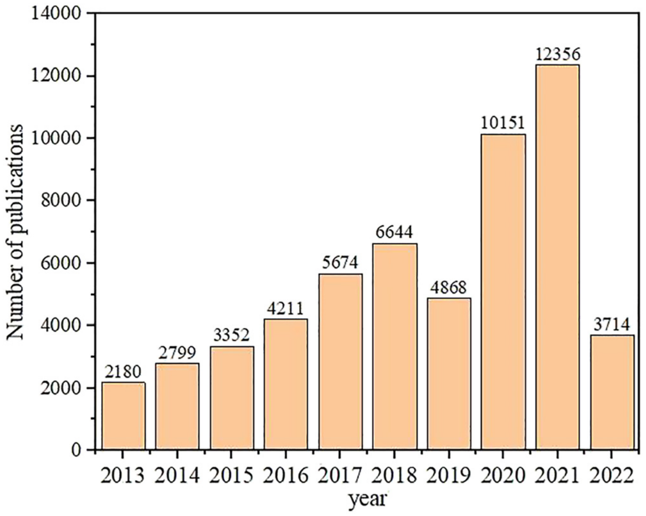

Fig. 1. Statistics of publications on using nanofluids in different applications from 2013 up to the present (considering the Scopus database, accessed on March 18, 2022)

nanoparticles size, and shape. Therefore, ultrasonication to suspend nanoparticles may not be enough to produce a suspension stable for a long time [13, 14]. Obtaining homogeneous nanofluids requires using many techniques that ensure the suspension of nanoparticles for a long time, which contributes to increasing the thermophysical properties of the nanofluids. The other factors, such as volume fraction or concentration of nanoparticle, shape, the nanofluids temperature, and type of nanomaterial play a significant role in enhancing thermal characteristics [15, 16].

The stability of nanofluids for the long-term returns to the ability of nanoparticles to suspend in the base fluid, which is positively reflected in the thermal conductivity of nanofluids. The effective dispersion of nanoparticles into base fluid help increase the thermal conductivity of nanofluids [17]. The addition of the surfactant has a significant effect on the stability of nanofluids, but an excess quantity of surfactant causes instability problems and affects the thermophysical properties such as density and viscosity of nanofluids as well as coverage of the particle surface, which make the heat transfer of particles poor [18]. The strong interactions of van der Waals cause the formation of aggregates of nanoparticles, representing a big challenge to obtaining stable nanofluids. Therefore, different techniques have been used to diminish this issue by applying a physical or chemical treatment such as adding a surfactant, using strong force to break the clusters of particles, and surface modification of the suspended particles, or using dispersing agents to disperse particles in the base fluid [19]. Despite the good properties of the nanofluid, some problems have been shown during their application, such as instability due to poor stability of nanoparticles in the base fluid, clogging, and low thermophysical properties [20].

The present review discusses and explains the factors that affect nanofluid stability, such as nanomaterial type, size of nanoparticles, type of base fluid and concentration ratio of nanoparticles on the thermophysical properties of nanofluids and their performance. We highlight the role of Brownian motion, adding surfactants and zeta potential, sonication duration, and pH in estimating nanofluid's stability. Then, more information is presented to improve the wide range usability of nanofluids and to prepare stable nanofluids that have good thermophysical properties.

2. NANOFLUID

Different types of nanoparticles are used, such as metals-based, carbon-based and nanocomposites, with various base fluids. Suspending nanoparticles in the base fluid produces a new fluid called nanofluid. In other words, it is the colloidal suspension of nanoparticles with high thermal conductivity into the base fluids. Thus, the nanofluid produced due to mixing nanoparticles with base fluid has new properties that make it suitable for the required application [21, 22]. The main advantage of nanofluids is good thermal transport that enhances their thermal conductivity compared with conventional heat transfer fluids [23]. Nanofluids are distinguished by higher heat transfer characteristics than commonly used fluids [24]. Improving the heat transfer of nanofluids depends on the different factors that could control their thermal properties. In preparing nanofluids, some parameters must be considered, such as volume fraction, type of nanoparticles, disperse, type of base fluid, nanoparticles' concentration, and added surfactants. Different types of nanoparticles with varying base fluids have been used, as shown in Fig. 2, where each nanoparticle has different thermophysical properties. Nanoparticles can be found in various shapes, such as cylinders, spheres, tubes, and rods, designed according to the required applications.

3. PREPARATION OF NANOFLUID

Stability is an important advantage that nanofluids must possess; achieving that is not easy. It depends on several matters such as nanoparticle types, purity, size, and shapes. The base fluid type used and the degree of agglomerations affect the preparation of stable nanofluids. Different techniques are applied to obtain stable nanofluids, as shown in Fig. 3; these techniques are in common use and assist in achieving nanofluids stability by preventing nanoparticle agglomeration [26, 27]. Thus, to avoid the particles' agglomeration in the base fluid, stirring and then sonication is applied to prevent any particle agglomeration that might form during mixing nanoparticles in the host fluid and to enhance nanofluid stability. Hence a stability agent is added to the suspension to avoid nanoparticle clusters. Furthermore, the reaction of fluid and stabilising agents produces an interfacial layer because of nanoparticle surface reactivity, directly influencing nanofluid functionality and properties. [28, 29]. Obtaining uniform, stable, long-lasting suspension depends on the chemical compatibility

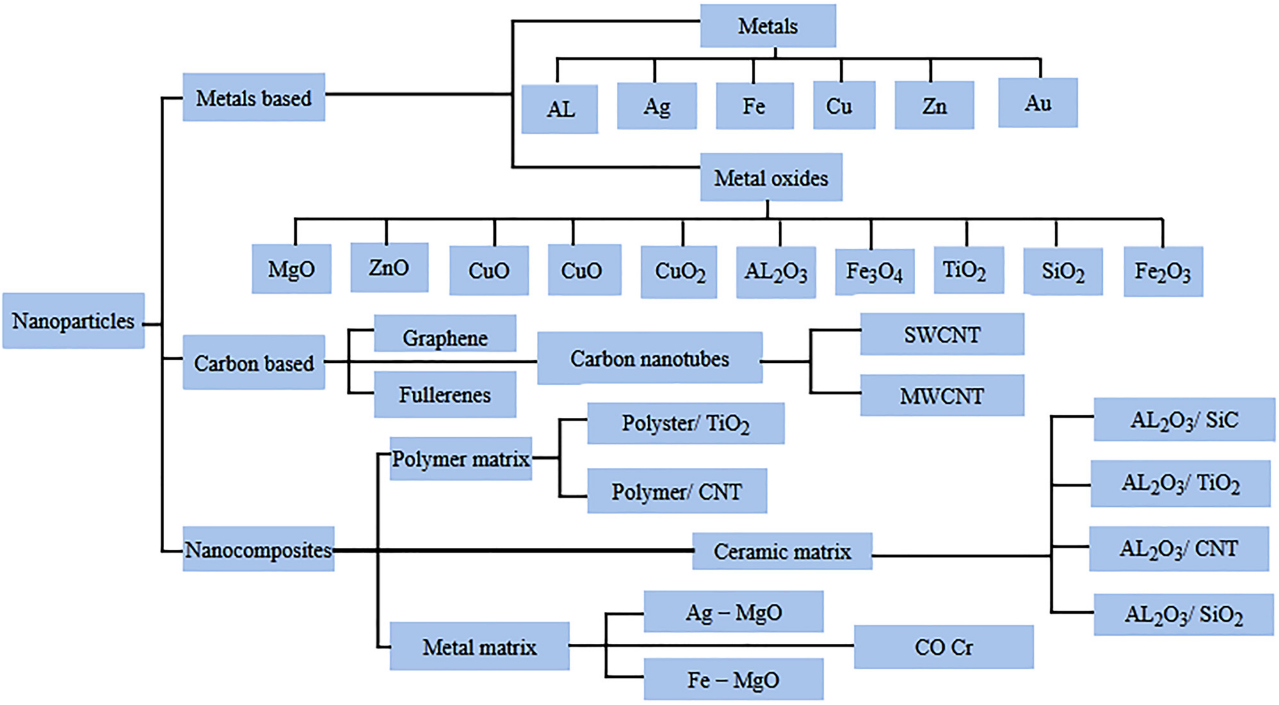

Fig. 2. Types of nanoparticles. Republished from [25], under Creative Commons Attribution 4.0

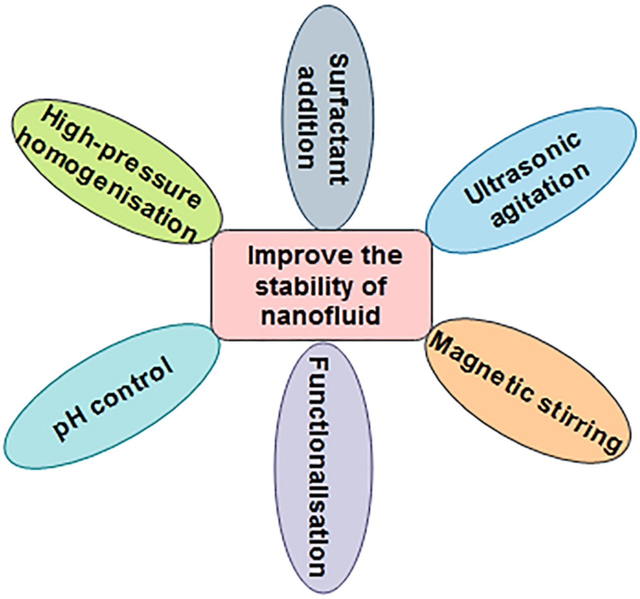

Fig. 3. Techniques used to improve the stability of nanofluid

pH, and the high dispersion of nanoparticles with the type of base fluid used [30]. Surfactants or dispersing agents that are added during the nanofluids preparation also control nanofluid thermal transport properties and performance [31]. Nanofluids are prepared using either one-step or two-step methods, representing common methods used to prepare nanofluids that influence nanofluid thermal transport and properties [32].

3.1. The one-step method

The low ability to agglomerate nanoparticles characterises this method [33]. In this method, two techniques are used; first, liquid chemical deposition directly formulates nanoparticles characterised by low agglomeration of nanoparticles. Preparing and dispersing the nanoparticles into the host fluid are rapidly done with neglected processes such as storage, transportation, and drying [34, 27]. The second one is physical vapour deposition to prepare stable nanofluid, using the physical Vapour Deposition technique condensing nanoparticles carried in the base fluid and reducing the accumulation of nanoparticles. The disadvantages of this technique are being costly and the residual reactants in the nanofluids [35]. A study conducted by [36, 37] found that the nanofluids prepared by the one-step method have improved dispersion and stability of mixing but contain impurities that form due to incomplete reactions. Thus, it is complicated and not feasible for mass production.

3.2. Two-step method

After producing nanoparticles as a nano-sized dry powder, using either physical or chemical methods, nanoparticles are dispersed into the base fluid to obtain nanofluid by using some techniques mentioned in Fig. 4 [38]. Two steps are commonly used to prepare nanofluids by dispersed nanoparticles using ultrasonication and agitation or stirring. This method is more suitable for large-scale production and more economical [39]. The main disadvantage of the two-step method is an agglomeration of nanoparticles, thus lowering the stability of the nanofluids. The colliding of the particles

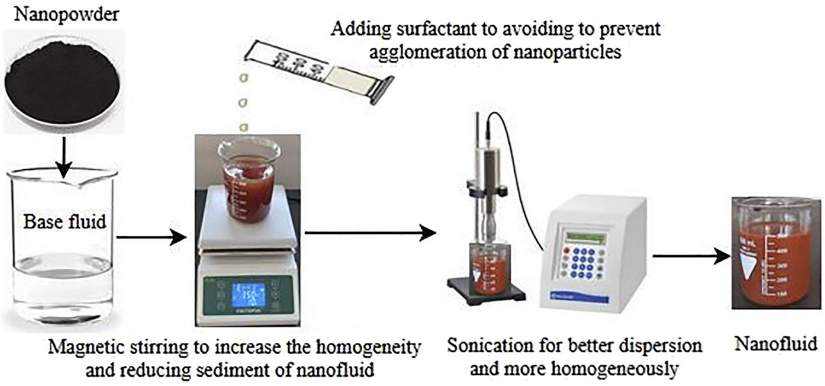

Fig. 4. Preparation of nanofluid by using two-step method

due to Brownian motion and strong van der Waals interaction causes cluster formation in the base fluid, which negatively reflects nanofluid stability [40, 27]. Some techniques mentioned in one-step are used to reduce or avoid nanoparticle agglomeration in the base fluid. The surfactant added to nanofluids is used to prevent nanoparticle aggregation.

4. STABILITY OF NANOFLUID

Nanofluids stability represents the sustenance of their performance for a longer time retaining their properties without clustering and nanoparticle aggregation in the base fluid [29]. Nanofluid stability is an intrinsic issue for engineering applications and represents a big challenge for researchers [41, 42]. Despite the small size of nanoparticles, gravity is the main reason for the instability of nanofluids, in addition to kinetic energies resulting from Brownian motion that make it not a suspension for a long time [43]. The adherence of dispersed particles in the base fluid causes the particle aggregates to settle due to gravity [44]. The preparation of nanofluids' influences their' stability; using the one-step method is more stable than the two-step method, and the synthesis techniques have an influential role in incrementing the fluid stability [45]. The random motion of nanoparticles in the base fluid due to Brownian motion and the interaction with neighbouring particles causes clustering, gradually increasing the agglomerations under gravity's effects, making nanofluids unstable [46]. Using not optimum quantity of dispersant negatively affects the thermophysical properties of the nanofluids and the degradation of chemical stability. Nanofluid stability requires applying techniques such as ultrasonic vibration, which is commonly used, surface modification, and surfactants that contribute effectively to nanofluid stability for long-term and at appropriate cost. The reduction of the concentration of dispersed nanoparticles in the base fluid positively influences the nanofluids' stability [47]. The sedimentation method is used to figure out the stability of nanofluids' stability by measuring the sediment (weight or volume) of particles under an external force field in the nanofluid, which helps define the stability of nanofluids.

The nanofluid is considered stable when the supernatant particle size concentration remains constant [34, 48]. The regulation of the fluid pH is one of the methods used to increase the stability of nanofluids by creating a surface charge around the nanoparticle that produces strong repulsive columbic forces that assist in particle dispersion [43]. Zeta potential is one of the factors used to define nanofluid stability by measuring the electrical potential (degree of repulsion) between small van der Waals forces and dispersed particles. Thus, the high zeta potentials, regardless of whether positive or negative, make nanofluid stable, as opposed to lowering zeta potentials, which causes clustering and sedimentation of nanoparticles [27]. Obtaining homogeneous thermophysical properties depends on the nanofluid's stability; when the van der Waals force is less than the electrical double layer repulsive force, it gives a stable nanofluid [49]. Using sonication and the addition of surfactants or dispersants are methods to improve nanofluid stability, [50] contributing to avoiding the agglomeration of nanoparticles and lowering the base fluid's surface tension. The stability of nanofluids is controlled by several factors, type of base fluid, sonication time and surfactant addition. The conventional base fluid has a dielectric constant such as ethylene glycol, benzene, hexane, ethanol, and water, which is directly proportional to the repulsive potential; thus, increasing the constant dielectric means more stability. Water has the highest dielectric constant compared with other base fluids, which means high repulsive potential and stability [51]. Implementation of a sonication bath or sonication probe by nanofluids contributes to breaking the nanoparticle cluster, more dispersed nanoparticles in the base fluid, and cluster size reduction, producing stable nanofluids and enhancing the thermo-physical properties [51]. Surfactant addition is one factor that helps decrease the interfacial tension and the average particle cluster size with time by electrostatic stabilisation [53]. Table 1 shows the factors influencing the stability duration of nanofluids used in different nanoparticle nanofluids.

Table 1. The main factors affect the stability duration of nanofluids

Ref.	Nanoparticles	Base fluid	Sonication time	Dispersant	Stability duration
[54]	Fe_3O_4	water	25 min	nonylphenol ethoxylate nonionic	25 days
[55]	ZnO	EG	3hours + stirring	non	6 h
[56]	TiO_2	water	60 min	Acetic acid	35 days
[57]	CuO	DI water	270 min	SDS	45 days
[58]	CNT	water	20 min	SDBS	30 days
[59]	Ag-MWCNT	water	40 min	non	40 h
[60]	Cu	water	15 min	CTAB	7 days
[61]	Al_2O_3	water	180 min + stirring	SDS	16 days
[62]	stainless steel	water	60 min	SDBS	10 days
[63]	Ag	silicon oil	60 min	Oleic acid	30 days

5. FACTORS AFFECTING THE STABILITY OF NANOFLUID

5.1. Brownian motion

The cluster formation of nanoparticles in the base fluid represents a problem intrinsically for nanofluids produced by the collision of particles with each other due to Brownian motion [40]. The collision of the particles with a high velocity with others moving slowly in the fluid causes uncontrollable particle motion due to thermal diffusion, which leads to Brownian motion. The nanoparticles are constantly colliding due to Brownian motion because large surface areas have high activity. Some factors such as smaller particle size, lower viscosity, and temperatures increment increase Brownian motion [64–67]. Nanoparticles of extremely small sizes are characterised by higher kinetic energies due to Brownian motion. However, it still suffers from not keeping suspension in the base fluid for a long time, which affects nanofluid stability [48].

The nanoparticles forming the solid stage interact with neighbouring particles when Brownian motion is constant, which causes strong, attractive forces for the nanoparticles. Hence, gradually increasing agglomerations with gravity influence made the nanofluids unstable [27]. Changes in nanofluid temperature have directly influenced Brownian motion, affecting nanoparticles such as thermal interactions, particle collisions, and diffusion [68]. On the other hand, increasing the cluster mass causes decreasing Brownian motion during cluster formation, while sticking between nanoparticles increases cluster forming and thermal conductivity [69]. Therefore, Brownian motion significantly affects nanofluids' thermal conductivity enhancement among nanoclusters and nanolayers [70], which is considered significant in nanofluids.

5.2. Surfactants

The surfactants are important factors that work as a bridge between the nanoparticles and the base fluids; their activity depends on the type of nanoparticles and the base fluids. Surfactants have an efficient role by reducing the interfacial tension of nanoparticles suspended in the base fluid and incrementing repulsive forces between nanoparticles [71]. The surfactants or dispersants are commonly used to prevent or reduce the agglomeration of nanoparticles via lowering the surface tension of base fluids, leading to improving nanofluid stability. The addition of surfactants contributes significantly to enhancing nanofluid stability and avoiding nanoparticle sedimentation. Increased use of surfactants negatively affects the thermophysical properties as low thermal conductivity and nanofluids' chemical stability [45, 47].

The feature of using surfactants and additives with nanofluids is to prevent the precipitation of nanoparticles in the base fluid. The clustering is affected by other factors, such as the viscosity and properties of the base fluids [46]. At high temperatures, some disadvantages could appear with surfactants, and pH regulators, which influence nanofluid stability, such as stabilisers breaking down, which causes changes in liquid properties, viscosity, and liquid surface tension. Surfactant is characterised by a lower thermal conductivity than the base fluid, affecting the thermal conductivity of nanofluids [71]; using surfactant in optimum concentration is important.

5.3. Zeta potential (ζ)

Zeta potential is an important factor in estimating the long-term or short-term stability of nanofluids, depending on the zeta potential value, as shown in Fig. 5 [73, 74]. Zeta potential is used to determine colloidal solution stability, and nanofluids are one of these solutions [75]. The zeta potential (electrical potential) refers to the degree of repulsion between charges of particles dispersed in the fluid. An increase in zeta potential value means the dispersed particles' robust columbic repulsion forces are higher when the attractive value of van der Waals forces is small. Therefore, nanofluids are called electrically stable when the zeta potentials are higher, regardless of whether negative or positive, while low zeta potentials lead to clustering and sedimentation of nanoparticles [27]. The electric potential that is generated between dispersant of the stern layer and a base fluid layer which is adhesive by the molecule surface, could determine by zettameters [75] where the value of zeta potential works as a function of pH [65]. The values of zeta potential change according to pH values [76].

Surfactants influence the zeta potential of nanoparticles, which increases the value of zeta potential with increased

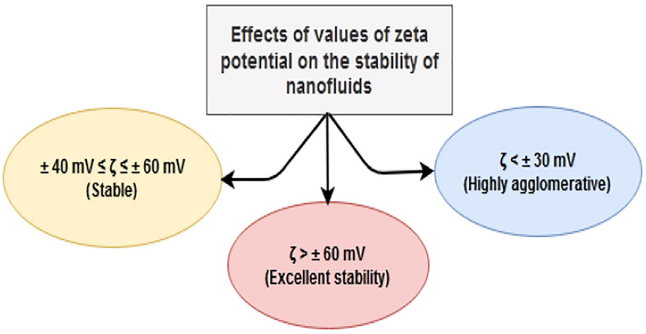

Fig. 5. Effects of zeta potential values on nanofluid stability

surfactants [71]. The pH negative and pH positive solution determines the zeta potential values; at lower pH, the zeta potential value is negative and vice-versa [77]. In other words, the repulsive interaction energy mainly depends on the zeta potential (surface energy and surface area) [78, 79], which is changed with the particle shape. Thus, zeta potential analysis is an important and common technique to estimate nanofluid stability or instability.

5.4. Effect of pH

pH (potential hydrogen or also called power hydrogen) is used to evaluate the acidity or the basicity of the solutions; pH is an important element that assists nanofluid stability and depends on the zeta potential [77, 80]. Regulating fluid pH helps improve nanofluid stability by controlling the particles' surface charge. The creation of surface charge causes an electrical double-layer that covers the nanoparticle and permits the production of repulsive Coulombic forces, helping article dispersion [81]. Nanofluid thermal properties change with variation of pH [82]; thus, pH constitutes an important factor in determining thermal conductivity and nanofluid stability [83]. Several studies were conducted about the effects of pH variation on nanofluid dispersion stability and other properties.

A study used some surfactant types (SDBS) with adding hydrochloric acid (Al_2O_3 and Cu/base fluids) to control the pH value. It found that the viscosity of Al_2O_3-based fluids was higher than that of Cu-based fluids at the same pH value and weight fraction. It produces stable nanofluids with specific pH ranges for Al_2O_3 at 7.5 and 8.9, for Cu at 7.6. In contrast, decreasing the pH value to 7, both Al_2O_3 and Cu suffered from the agglomerate then fast sedimentation, thus instability of nanofluids [84]. While Ghadimi [43] indicated that to increment the mass fraction of nanoparticles at a pH of 8 contributes to enhancing nanofluid stability and thermal conductivity.

5.5. The effect of the shape and size of nanoparticles

The shape and size of nanoparticles play an essential role in nanofluid stability and thermophysical properties. The nanoparticles of small size and high concentration in base fluid contribute to the improved thermal conductivity of nanofluids [85]. In contrast, a limited impact is found in the shape and size of nanoparticles on nanofluid density [86]; increasing the size and type of nanoparticles influences the thermal behaviour of nanofluids; thermal conductivity is mainly associated with type and size of nanoparticles, where the small size nanoparticles increase thermal conductivity [87, 88]. The small nanoparticle size and increased temperatures increase Brownian motion [64–67]. The small nanoparticles are characterised by higher kinetic energies due to Brownian motion, which causes the instability of nanofluids due to gravity [43]. Another study by [85] found that the shapes of nanoparticles affect nanofluid stability and thermal conductivity. The nanoparticles with cylindrical shapes have less influence on the thermal conductivity of nanofluid than those with the spherical shape. Thus, the shape, size, and type of nanoparticles are important factors in obtaining stable nanofluids.

6. THERMOPHYSICS PROPERTIES OF NANOFLUIDS

Mixing nanoparticles into the base fluids causes changes in the thermophysical properties of the mix because both nanoparticles and base fluids have different properties. Nanofluids' thermophysical properties are significant factors contributing to enhancing their properties and positively reflecting their performance. Several studies have investigated the effect of nanofluids' thermophysical characteristics on their performance, the effects of some parameters on the nanofluids thermophysical properties, such as temperature, base fluid, volume fraction, nanoparticle concentration, etc. Therefore, this section will discuss each mentioned parameter's influence on each thermophysical property of nanofluids.

6.1. The density of the nanofluid

Density is an essential property of the nanofluid that significantly affects the thermal system's sustainability and achieves a suitable extent of nanofluid stability [89, 90]. Nanofluid density is affected by increased mass fractions and reduced temperature. Thus, an increase in density affects the pumping capacity by increasing power consumption, specifically in thermal applications [91, 92]. Using surfactant contributes to a limited increase in nanofluid density [93], while nanofluid density increases with the mass fraction increase [94, 95]. On the other hand, increasing the density of nanofluids has a negative impact on the Reynolds number by boosting the friction factor [96]. Increased temperatures lead to a low density of nanofluids [97] while nanoparticle concentration is increased [98, 99]. The base fluid plays an essential role in nanofluid density [100], while the number of nanoparticles and the surfactant added have less effect on nanofluid density. A limited effect was found for nanoparticles' shape and size on nanofluid density [96]. Equation (1) is commonly used to determine nanofluids' density, which depends on the volume fraction of nanoparticles, the base fluid density, and the density of nanoparticles.

$$\rho_{nf} = \varphi\rho_{np} + (1-\varphi)\rho_{bf} \quad (1)$$

6.2. Specific heat of nanofluid

Specific heat represents an important property of any thermal fluid, representing the thermal contrast for a certain substance at a particular amount of heat; this property plays a vital role in providing the energy that transmits from one body to another [101]. In nanofluids, specific heat is different depending on the nanomaterials used, their concentration in the base fluid, and the type of base fluids [102]. Nanofluids' specific heat increases with the increasing of temperature while lowering at increased volume fraction [103]. Thus, there is an inverse relationship between the specific heat and volume concentration. The specific heat of nanofluid decreases with increasing volume concentration and increases with rising temperature [104].

Despite using different types of nanoparticles and a variety of nanoparticle size, the specific heat dropped and appeared to have an unstable behaviour increasing the volume fraction [105–107]. Adding a small concentration of nanoparticles dispersed in the base fluids enhanced the specific heat regardless of the particle shape or type [108]. A study by [109] found no change could occur with nanofluids' specific heat by adding a little surfactant, and increasing the surfactant amount will cause an increase in the specific heat. The nanofluid's specific heat is determined using the equations in Table 2.

6.3. Thermal conductivity of nanofluid

One of the most important nanofluid properties in the heat transfer field is thermal conductivity. Increasing the thermal conductivity of nanofluids is required to enhance the heat transfer of nanofluids [112]. Conventional fluids are poor in the field of heat transfer. Therefore, numerous experiments were conducted to improve the heat transfer by increasing the fluids' thermal conductivity. The addition of solid materials of nanoparticles into the base fluid enhances the high thermal conductivity of nanofluids [102, 113, 114]. Using nanoparticles with a higher thermal conductivity in the basic fluid will increase the thermal conductivity of nanofluids [115].

On the other hand, increment temperature and concentration of nanoparticles in the base fluid cause an increase in the thermal conductivity of nanofluid due to rising kinetic energy that produces the strengthening of the collision between particles [93–95, 116, 117]. Increased nanoparticle concentration and reduced particle size contribute to the improved thermal conductivity of nanofluids [118].

Table 2. The formula used to calculate the specific heat of nanofluid

References	Formula	Equation
[110]	$c_{p,nf} = \frac{\rho_{bf}(1-\phi)}{\rho_{nf}}c_{p,bf} + \frac{\rho_{np}\phi}{\rho_{nf}}c_{p,np}$	(2)
[99]	$C_{p_{nf}} = C_{p_{np}}\phi + (1-\phi)C_{p_{bf}}$	(3)
	$C_{nf} = \frac{\rho_{np}\phi C_{p,np}+\rho_f C_{p,f}(1-\phi)}{\rho_p\phi+\rho_f(1-\phi)}$	(4)
[111]	$C_{p,nf} = \frac{\phi\cdot(\rho_{nf}C_{p,n})+(1-\phi)-(\rho_{bf}C_{p,bf})}{\rho_{nf}}$	(5)

The thermal conductivity of nanofluids mainly depends on the volume concentration of nanomaterials in the base fluid, the type material of nanoparticles, and their size [87]. Another increase in thermal conductivity could be by breaking the particle agglomerates after subjecting the nanoparticles to a long ultra-sonication period leading to increases in particles' splits and enhancing the base fluid's suspension nanoparticles [86]. The smaller nanoparticles contribute by increasing the thermal conductivity [88]. The shapes of nanoparticles have a role in increasing the thermal conductivity, whereas spherical nanoparticles have better thermal conductivity than cylindrical shapes [85].

Different parameters could affect nanofluids' thermal conductivity, such as adding the surface modifiers leads to a lower thermal conductivity of nanofluids [119]. The studies indicate that adding surfactant material has limited influence on the thermal conductivity of nanofluids, achieving a slight decrease in thermal conductivity by increasing the surfactant quantity [97]. Mehmood R. [120] observed that nanoparticles' instability in the base fluid causes agglomerates in the nanofluid, and it is one of the reasons for decreasing thermal conductivity. Many theoretical models and correlations have been developed to determine thermal conductivity; Table 3 indicates some formulas used to quantify nanofluids' thermal conductivity.

6.4. Viscosity of nanofluid

Viscosity represents the essential factor that significantly affects the nanofluids' behaviour [126]. The fluid's viscosity influences heat transfer characteristics, where increased viscosity represents the main obstacle for circulating nanofluids in the pumps' systems [95]. Increasing the nanoparticle concentration causes an increase in nanofluid viscosity, which leads to an increase in pumping power due to pressure drop [96, 127]. Meanwhile, surfactant addition somehow increases nanofluid viscosity [97, 128]. Examining the thermophysical

Table 3. The formula used to determine the thermal conductivity of nanofluid

References	Formula	Equation
[121]	$\frac{k_{eff}}{k_f} = 1 + \frac{n(\beta-1)\phi}{(\beta+n-1)-(\beta-1)\phi}$	(6)
[122]	$\frac{k_{eff}}{k_f} = 1 + \frac{3(\beta-1)\phi}{(\beta+2)-(\beta-1)\phi}$	(7)
[123]	$k_{nf} = \frac{1-\phi+2\phi\frac{k_p}{k_p-k_f}ln\frac{k_p+k_f}{2k_f}}{1-\phi+2\phi\frac{k_f}{k_p-k_f}ln\frac{k_p+k_f}{2k_f}} \times k_f$	(8)
[124]	$k_{nf} = \phi k_p + (1-\phi)k_{fb}$	(9)
[125]	$\frac{k_{nf}}{k_{bf}} = \left(\frac{k_{np}+2k_{bf}+2(k_{np}-k_{bf})(1+\beta)^3\varphi}{k_{np}+2k_{bf}-(k_{np}-k_{bf})(1+\beta)^3\varphi}\right)$	(10)

properties of nanofluids by [129] showed that volume concentration and temperature control viscosity. Simultaneously, the base fluid is the most important factor determining nanofluid viscosity. Thus, high thermal conductivity with low viscosity must be attained by the ideal nanofluids. In contrast, nanofluid viscosity becomes lower with increasing temperature [130].

Increasing temperature contributes to increasing thermal conductivity, which leads to lower viscosity and reduces agglomeration of the nanoparticles [96]. Thus, both [131, 132] indicated an increase in nanofluids' thermal conductivity with temperature increase, while the opposite occurred with viscosity. Eq. (12) is used when the volume concentration is low ($\phi \leq 0.02$), while Eq. (11) is proposed when volume concentration is up to 4%. Eq. (14) is valid until 40% of the volume fraction, and for suspension of spherical, non-deformable particles Eq. (15) is used, Eq. (13) is proposed for suspension of spherical as well as rigid particles. Thus, Eq. (16) could be used instead of Eq. (11) for both spheres of wide and equal sizes; Table 4 shows the formulas used to determine nanofluid viscosity.

7. EFFECT OF BASE FLUID ON THE NANOFLUID

The base fluid is considered an essential factor affecting nanofluid heat transfer characteristics [85]. The base fluids' thermal conductivity substantially impacts the thermal conductivity of nanofluids [139]. Most base fluids have low thermal conductivity; thus, mixing nanoparticles with base fluids enhances their thermal conductivity and makes them effective for heat transfer applications [140]. The viscosity of base fluid plays an essential role in the Brownian motion of nanoparticles, affecting nanofluids' thermal conductivity properties. [40]. The base fluid is a base on which the nanoparticle is distributed. Hence, different factors are considered when choosing the base fluid, such as viscosity, heat capacity, thermal stability, freezing point, etc., to obtain the best performance [141]. Several studies found that the base fluids have a more important influence on nanofluid properties, particularly on density, than other nanoparticle properties such as nanoparticles' size or shape [142, 130]. Water is considered suitable for nanoparticles as a base fluid because it has a good suspension with acceptable heat transfer and is economically appropriate.

Table 4. The formulas used to determine the viscosity of nanofluid

References	Formula	Equation
[133]	$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}}$	(11)
[134]	$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 2.5\phi$	(12)
[135]	$\mu_{eff} = (1 + 2.5\varphi + 6.5\varphi^2)\mu_f$	(13)
[136]	$\mu_{nf} = \mu_{bf}(1 + 4.5\varphi)$	(14)
[137]	$\mu_{nf} = \mu_{bf}(1 + 2.5\varphi + 4.75\varphi^2 + \ldots)$	(15)
[138]	$\mu_{nf} = \mu_{bf}\frac{1}{(1-1.35\varphi)^{2.5}}$	(16)

In contrast, using different base fluids other than water as ionic and oil liquids or a mixture of ethylene glycol-water in solar applications as an alternative medium results in better performance [143]. The nanofluids that use water as base fluid have thermal conductivity directly proportional to temperature and nanoparticle concentrations. Whereas in the case of nanofluids with ethylene glycol as base fluid, the nanoparticle concentrations will affect thermal conductivity more than temperature [144]. The use of water as base fluid with applications that are characterised by high temperatures is preferred. On the other hand, it is preferred to use ethylene glycol as the base fluid in nanofluids when adopting high nanoparticle concentrations [145]. Liquids such as water, pump oil, and kerosene are widely used, but they have low thermal conductivity, thus influencing the heat transfer process when used [1]. The different types of base fluids used are shown in Fig. 6. Researchers use more than one type to mix base fluids to achieve the best results. When selecting base fluids, some criteria should be considered [146]:

1. The base fluids should not react or degrade with added nanoparticles and not cause the agglomeration of nanoparticles.
2. The base fluid should prevent corrosion of the pipes that carry it or the material of equipment used.

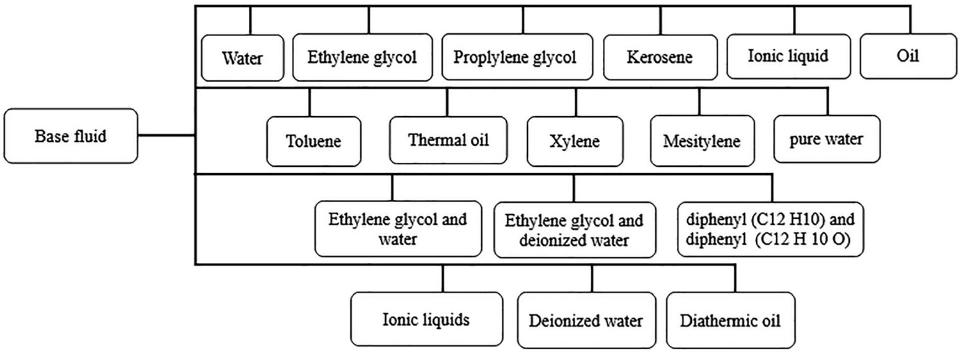

Fig. 6. Types of the base fluids

3. Selected base fluids must be appropriate to the pump power requirements because of the nanofluid viscosity determined by the base fluids' viscosity.

8. THE LIFE CYCLE ASSESSMENT OF NANOMATERIALS

The life cycle assessment (LCA) is an essential tool for evaluating the environmental effect of manufactured nanomaterial (MNMs) throughout their complete life cycles. The LCA depends on the concept of life cycle thinking, which considers a systematic method for evaluating the possible environmental impacts of products, such as services and processes, during their whole life cycles [147]. In the past decade, many articles dealt with the LCA to nanotechnology [148, 149] by considering the LCA to nanotechnology applications. The results indicated similar conclusions stating some challenges for modelling and evaluating the LCA nanotechnology, such as the lack of (average) life cycle inventory (LCI) data for producing the most relevant MNMs. There is a shortage of average life cycle inventory data for the MNMs and a lack of characterisation factors for MNMs, which is essential to account for MNMs for assessing the life cycle impact of LCA. A study by [150] discussed the LCA methodology's basis as life cycle inventory, goal and scope definition, life cycle impact assessment, goal and scope definition and system boundary to highlight limitations, progress, and current practices facing LCA application of MNMs. It found a comprehensive lack in the environmental impacts of MNMs; the study has recommended presenting more detailed LCA data within MNMs studies. Then increasing the efforts to evaluate the environmental impacts and risks of MNMs of their whole life cycle, including the end-of-life stages. No clear rules help to account for the final releases of MNMs in inventory modelling. According to the standard ISO-14040 2006, the LCA consists of the extraction of raw materials, manufacturing, uses, and end-of-life [151]. None of the LCA studies is compliant with ISO because none covers the availability for the whole life cycle of nanomaterials or engineered products.

9. CRITICAL ANALYSIS

To prepare stable nanofluids that work for a long period is not a simple method; it requires controlling the factors that influence nanofluid properties and their thermal behaviour. During the review, a few shortcomings were noticed that can be summarised as follows:

- The preparation of stable nanofluids for a long time depends on the preparation methods. The one-step produces stable nanofluids due to good dispersion that causes low agglomeration of nanoparticles, but it is costly and not feasible for mass production and contains impurities that form due to incomplete reactions. The two-step method is useful to prepare nanofluids for large-scale production and economical but suffers from nanoparticle agglomeration, thus requiring different techniques to improve nanofluid stability.
- Nanoparticles' aggregation results from the random motion of nanoparticles in the base fluid because of Brownian motion, and the interaction with neighbouring particles causes clustering under the effects of gravity, which causes unstable nanofluids. Despite the small sizes of nanoparticles, the adherence of dispersed particles in the base fluid causes the particle aggregates to settle due to gravity. Thus, added surfactants or dispersants contribute effectively to nanofluid stability, but using not optimal amount of dispersants or surfactants negatively affects nanofluid's thermophysical properties and the degradation of the chemical stability of nanofluids.
- The high zeta potentials, regardless of whether positive or negative, make nanofluids stable, and the value of zeta potential increases with added surfactants. In contrast, lowering the value of zeta potentials causes clustering and sedimentation of nanoparticles in the base fluid and affects nanofluids' thermophysical properties. Other disadvantages of surfactants and pH regulators at rising temperatures, such as the breakdown of stabilisers, influence nanofluid stability.
- Some parameters positively affect and others negatively affect the thermophysical properties of nanofluids. Nanofluid density and viscosity decrease with temperature increase while increasing added surfactants and nanoparticle concentration requires high power for their circulation. Increased nanoparticle concentration negatively impacts nanofluids' specific heat, while rising temperatures enhance nanofluids' specific heat. Thermal conductivity improves at increased temperature and concentration with reduced particle size. Thus, nanoparticle concentration, surfactants, temperature, properties, base fluids, and nanoparticle size mainly control the thermophysical properties of nanofluids either negatively or positively.
- Most studies conducted on LCA suffer from a lack of life cycle inventory LCI and the characterisation factors for MNMs. There is a shortage of average life cycle inventory data for the MNMs and a lack of characterisation factors, which is essential to account for MNMs for assessing the life cycle impact of LCA.

10. CONCLUSION

Preparing nanofluids in one step results stable nanofluids, but it is unfeasible for large-scale production. On the contrary, two-step preparation allows large-scale production but suffers from the agglomeration of nanoparticles. Nanoparticles of a small size lead to the adherence of dispersed particles in the base fluid and then aggregates to settle in the base fluid due to gravity. Applying some techniques such as ultrasonication, adding surfactants, and regulating the fluid pH contribute effectively to the stability of the nanofluid. Furthermore, an uncontrolled collision of the high-velocity particles with others moving slowly in the fluid due to Brownian motion causes cluster formation of nanoparticles in the base fluid, leading to unstable nanofluids. Nanofluid's thermophysical properties and the factors affecting nanofluid stability play an intrinsic role by enhancing the performance of nanofluids, thus positively reflecting on nanofluid applications. Rising temperature leads to improved thermal conductivity and specific heat but decreases the density and viscosity of nanofluids. In contrast, increased nanoparticle concentration causes an increase in density, the viscosity of nanofluids, and thermal conductivity. The size of nanoparticles with their concentration in base fluids has a negative impact on the specific heat. For the LCA, most of the studies of ENMs are ISO-compliant due to none covering the whole life cycle of nanomaterials because of the shortage of average life cycle inventory data and a lack of characterisation factors of the MNMs which affect the LCA of nanoparticles.

NOMENCLATURE

ϕ	The volume fraction of nanoparticles
ρ_{np}	The density of the nanoparticles
$c_{p,nf}$	Specific heat of nanofluid
ρ_{bf}	The density of the base fluid
ρ_{nf}	Nanofluid density
μ_{nf}	Dynamic viscosity of nanofluid kg m^{-1}
μ_f	Dynamic viscosity of base fluid kg m^{-1}
μ_{eff}	Effective viscosity of nanofluid
n	Empirical shape factor ($n = 3/\Psi$)
Ψ	The ratio surface area of a spherical and the non-spherical particle
β	The ratio of the thermal conductivities ($\beta = k_s/k_f$)
k_{eff}	The nanofluids effective thermal conductivity
K_s	The thermal conductivities of the solid phase
K_f	The thermal conductivities of the fluid phase
K_p	Nanoparticles thermal conductivity
k_{nf}	Thermal conductivity of nanofluid

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