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Review Article

REVIEW AND EVALUATION OF NANOFLUIDS AS PROSPECT THERMAL ENERGY STORAGE MATERIAL FOR CONCENTRATED SOLAR POWER APPLICATION

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Abstract

Solar energy intermittency is one of the main challenges encountered by thermal energy storage systems in concentrated solar power plants due to the low heat transfer rates during charging operations. The critical thermophysical property to be considered for combating this problem is the thermal conductivity. Thus, base fluids with dispersed nanoparticles, better known as nanofluids, have become materials with great potential since they enhance efficiency during charging intervals by increasing the charged material's thermal conductivity by up to 89 %. By gathering and analyzing results from various studies in nanofluids, it was observed that there is a considerable improvement in the thermal storage material compared with the base fluid alone. There is also an increase in the thermal conductivity as nanoparticles are added. Obtaining an increase as great as 99 % allows faster rates of heat transfer. Overall, this may significantly improve the efficiency of thermal energy storage systems in concentrated solar power plants.

Keywords: Solar energy, Concentrated solar power, Thermal energy storage, Nanofluids, Nanomaterials, Thermal performance enhancement.

1. Introduction

The solar energy systems have the most important role among other renewable energy systems because solar radiation is ample in many areas around the world [1]. The nuclear fusion reaction existing at the core of the sun is continuously discharging a substantial amount of solar radiation towards the Earth. Perhaps solar energy alone can sustain the world's total energy demands if the solar radiation is fully harnessed [2].

In solar energy technologies, the concentrating solar power is the current most advanced and developed technology regarding commercial exploitation due to its high efficiency and can readily be integrated with thermal energy storage systems [1].

Concentrating solar power (CSP), also termed as concentrated solar power or simply solar thermal power, is the most likely candidate to cope with the challenges encountered by conventional power plants. Among the other renewable energy systems, CSP systems are found to be one of the promising solar thermal technologies due to their cost-effectiveness. They are fuel independent. Their supply is unrestricted since the energy generated is coming from the sunlight through the conversion of solar energy to thermal energy [3].

CSP systems are entirely dependent on solar radiation in generating electricity. However, the radiation from the sun is intermittent and unpredictable; thus,

making solar energy technologies, specifically CSP systems, is unreliable [4]. Integrating solar thermal energy storage to CSP systems may overcome the intermittency or unpredictability of solar energy and ensure a balance between the energy supply and energy demands [1].

Thermal energy storage (TES) is extensively and commonly utilized in CSP systems. It is a prominent solution method for the difficulties experienced by renewable energy systems, specifically solar energy, due to daily and seasonal fluctuations, causing the systems to be unreliable. The reliability of solar energy can rise by storing excess energy during the day. The stored energy can be used whenever needed [5]. When the TES system is integrated into the CSP plant, it reduces the mismatch between energy demand and supply. It causes an increase in terms of the reliability and performance of solar energy technologies, specifically CSP systems [6].

The utilization of solar energy technologies has been continually expanding throughout the world. However, the performance of most of these technologies has already reached its limit. Various studies claimed that the reason in limiting the performance of solar energy technologies is due to the working fluids used in the transportation and conversion of energy [7].

In CSP applications with integrated TES system, the commonly used thermal storage material (TSM), such as water, ethylene glycol, thermal oils, and molten salts, acquires a relatively low thermal conductivity [8]. Thermal conductivity is one of the critical properties considered in a working fluid. It dramatically affects the overall efficiency of the system, especially in heat transfer [9]. Thus, thermal storage materials with low thermal conductivity are unable to produce high heat transfer rates, reducing the system's energy storage capacity [10].

The development of nanotechnology has called great attention of scientists and researchers to make use of a new fluid called nanofluids as another method for enhancing the thermal properties of the working fluids conventionally used in thermal storage, CSP applications. Various researches and experimentations have seen the potential of nanofluids that can help improve the heat transfer characteristics of the working fluids [11].

Nanotechnology is a new advanced science that studies the molecular or atomic level of a material. It focuses on the nanostructured materials' syntheses, characterizations, explorations, and exploitations. Nanostructured materials refer to the materials with dimensions ranging from 1 to 100 nanometers on their structural elements, such as their molecules. These nanostructured materials are also called nanoparticles [12].

The performance of TES systems in CSP applications is highly dependent on the thermophysical characteristics of the TSM used. Thus, to achieve excellent performance, the fluid should acquire high thermal conductivity, high specific heat capacity, high heat transfer coefficient, and high critical heat flux. It is impossible to acquire all the characteristics mentioned above for the conventionally used fluids as TSM. However, the addition of a small number of nanoparticles can allow these conventionally used fluids to acquire all these excellent characteristics to achieve better performance [13]. The physical and chemical properties of the nanoparticles, such as thermal, electrical, optical, magnetic ones can be easily modified due to the increase of their surface area to volume. Therefore, fluids dispersed with these nanostructured materials or nanoparticles have more promising and unique properties compared to that of bulk conventionally used materials, having the same compositions [12].

Moreover, nanotechnology has vast potential applications, especially in the energy field, through improving energy efficiency, energy-saving, and energy storage [12]. It has helped mainly in solar thermal energy by coping with its constraints regarding the poor performance of some of the thermal properties, including the thermal conductivities and specific heat capacities of the used conventional fluids. These poor thermal properties greatly affect the efficiency of the TES systems. In 1995, a researcher had developed a new advanced fluid called nanofluid [9]. Nanofluids are a mixture of nanoscale materials also called nanoparticles having an average size of fewer than one hundred nanometers and a base fluid. A base fluid refers to the conventional working fluids used in TES systems such as water, molten salts, oils, etc. In producing a nanofluid, the base fluid is dispersed with metallic or nonmetallic nanoparticles by Brownian motion. Various researches and experimentations have shown that the dispersion of a relatively small amount of nanoparticles into the base fluid results in enormous improvement of the thermal properties of the storage medium, making it more advantageous in TES systems. Perhaps, storage medium acquiring high thermal capacity enables it to store relevant heat by using only a small volume of the storage medium; thus, reducing energy losses and costs [14].

This modern and advanced type of fluid was found to be a solution to the problems regarding the usage

of fluid with larger suspended particles as it causes clogging, abrasion, fouling, and rapid sedimentation. Also, the struggle of using fluids with micrometer-sized particles makes it uneasy to use them in small passages of some heat transfer equipment due to the formation of large agglomerates. Moreover, nanofluids have better thermophysical properties, especially thermal conductivity, which is associated with the heat transfer rates that are more desirable in solar thermal applications [15].

According to the research work of N. Ali et al., the thermal conductivity of conventional fluids, such as the different heat transfer fluids and organic materials, compared to the thermal conductivity of the metal and metal oxide nanoparticles is relatively low. Perhaps, the research findings showed that the copper nanoparticles tend to have a thermal conductivity of three thousand times greater than that of engine oil and seven hundred times greater than that of water. Similar findings were obtained from different fluids. Since the nanoparticles are in solid form, they tend to have better thermal properties, such as thermal conductivity, than that of the base fluid, which is in liquid form. Hence, when nanoparticles are dispersed into the base fluid, there would be an overall increase in heat dissipation, followed by the improvement of nanofluid thermal conductivity. Thus, it was concluded that dispersing some nanoparticles into a base fluid is expected to enhance the thermal properties in line with the heat transfer rates of a working fluid. The dispersed nanoparticle itself acquires a substantial thermal conductivity in contrast to the commonly used working fluids [9].

This research aims to provide a comprehensive and reliable list of data only from sources gathered from different journal articles on studies related to nanofluids and other TSM. Also, the types of nanofluids used for comparison are metals and metal oxides. The novelty of this research review is in assessing previous studies on the nanofluids and their critical thermophysical properties that are advantageous for TES systems in CSP utilization. The already-conducted research has mainly leaned on increasing several characteristics such as thermal conductivity. In addition, this review would also tackle other factors that would make them highly similar to other persisting thermal storage materials in the CSP field.

2. Review methodology

This research review will assess the limitations of CSP applications, primarily on the TES systems. The relevant thermal properties of fluid that are advantageous in TES systems will be presented and evaluated.

This research review will attempt to gather various journal articles concerning nanofluids, along with their enhanced thermal properties. These articles are limited only to nanofluids with oxide and metal oxide nanoparticles. The data from the collected journal articles will be analyzed by comparing the desired thermal property parameters from the gathered data regarding the thermal properties of the nanofluids. The different factors that significantly affect the thermal properties and their limitations or reasons will be presented. Based on the gathered data, the nanofluid with the highest yield will be assessed and presented. Lastly, the evaluation of the gathered journal articles will be performed by identifying the deficiencies and research gaps for improvement.

3. Preparation of nanofluids

In producing nanofluids, uniformity of the dispersed nanoparticles, which is in line with the stability of the nanofluids, is one of the critical factors to consider; this is much dependent on how nanofluids are being prepared using different methods. Moreover, nanofluids have special conditions in their preparing and making, especially in dispersing the nanoparticles, such as durability, homogeneity, and physical and chemical stability. Therefore, it is not merely formed by a solid-liquid mixture [9].

When nanofluids are used in different applications, their stability or preparation with uniform dispersed nanoparticles have technical challenges [16]. It is due to the particles being dispersed into the base fluid with relatively smaller size and larger surface area, which causes the interactions between the particles to become dominant. In a nanofluid system, every particle experiences dissimilar types of interactions. The interaction may be experienced either in the particle-liquid system or in the particle-particle system. These interactions are caused by attractive and repulsive molecular forces on every particle surface. Among the other types of forces, the attractive molecular forces remain the strongest, causing the particles to become much closer. Thus, due to these attractive molecular forces, the particles tend to form a lump, referred to as agglomeration. The formation of agglomeration causes the poor stability of the nanofluids and prevents the homogenous dispersion of the nanoparticles [17]. In general, if the nanoparticles are unwell-stabilized into the base fluid, they will

stick with each other; thus, increasing the agglomeration of the particles. Agglomeration will result in the rapid sedimentation of the nanoparticles [18].

Moreover, the stability can affect the different thermal properties of the nanofluid, including the thermal conductivity, the specific heat capacity, viscosity, and density. As it was observed in various researches, nanoparticles dispersed in an unstable nanofluid always tend to contain large agglomerates. It was also found that the average diameter of the formed agglomerates of the nanoparticles could reach up to micron sizes. The size of the nanoparticles is one of the fundamental factors that must be considered upon estimating the thermophysical parameters of a nanofluid. Also, to ensure the production of a stable nanofluid, characterization analysis must be done at every step of preparation to acquire accurate results [17].

The preparation defines the stability of nanofluids. Also, to better understand the phenomenon of stable nanofluid preparation, the information regarding the production and various properties of the nanomaterial and base fluid will be crucial. There are two methods in preparing and producing nanofluids: the one-step method and the two-step method [17].

3.1. One-step method

The one-step method also termed as the bottom-up approach, uses a single step from simultaneously fabricating and, at the same time, dispersing the nanoparticles into the base fluid. This method also promotes the reduction of the agglomeration of nanoparticles by skipping the drying, transportation, storage, and dispersion of nanoparticles. As a result, the agglomeration of the nanoparticles is minimized, causing fluid stability to increase [19]. There are also other types of the one-step method, including phase transfer methods, submerged arc nanoparticle synthesis system (SANSS), grafting, thermal decomposition, vapour deposition (VP) methods, and microwave irradiation methods [17]. However, the most commonly used one-step method is the chemical vapour deposition [20] illustrated by Figure 1.
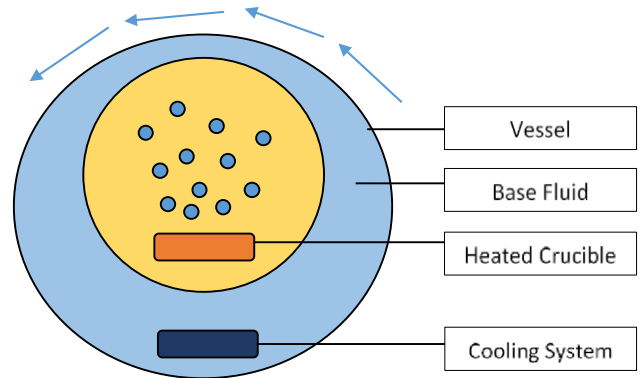
Fig. 1. Chemical Vapor Deposition synthesis of nanofluids

In the chemical vapour deposition synthesis of nanofluids, there is a rotating disk introducing a centrifugal force. It forms a thin layer of a base fluid at the vessel wall. Materials with large size particles are placed in a melting pot, heated, and evaporated. The evaporated bulk materials may be condensed; thus, forming nanoparticles. Once these nanoparticles are in contact with the thin layer of the base fluid, it will then start to disperse in the base fluid [21].

Moreover, certain nanofluids are prepared and created by using the one-step method only. These certain nanofluids are highly dependent on the properties of the base fluid used, the properties of the nanoparticles used, the interactions among the particles, and the requirement of the product application [17].

Using the one-step method in preparing nanofluids can provide excellent stability. It can obtain an extensive stable dispersion of the nanoparticles within the base fluid. As a result, the effect of agglomeration in the prepared nanofluids using the one-step method was found to be insignificant. Also, the structures of the nanoparticles can be easily manipulated by varying the synthesis parameters [19].

Regardless of its excellent Stability, the one-step method has multiple disadvantages. In terms of its application, nanofluids prepared by this method must only be used for processes with low vapour pressure. Controlling the structure and size of the nanoparticles that will be dispersed into the base fluid is very difficult [17]. Upon preparing the nanofluids, there are difficulties in disposing of the contaminants left in the nanofluids by the reaction process as the reactants are unable to transform into products completely. These impurities will be a hindrance to the accuracy of predicting the thermophysical properties of the nanofluids. Also, the one-step method is unsuitable to use in synthesizing nanofluids on a larger scale due to the high cost, making it an uneconomical method [19].

3.2. Two-step method

In the two-step method, also termed as the top-down approach, the nanoparticles dispersed in the base fluid are initially produced using different methods, such as sol-gel method, gas-phase condensation, mechanical methods, and liquid-solid-state reactions in the form of a dry powder. In most cases, the nanoparticles in the two-step method are synthesized and prepared using the gas-phase condensation method, specifically, the chemical vapor deposition (CVD) method. The CVD is performed under a noble gas atmosphere to convert nanoparticles into dry powders. The nanoparticles are then added and dispersed into the base fluid. A medium, or equipment, used: surfactants and ultrasonic vibrations, namely, magnetic stirrers, homogenizers, ultrasonic bath, bead mills, and high-shear mixers to ensure uniformity in dispersing the nanoparticles and decrease the agglomeration [18].

The two-step method is widely used in preparing nanofluids since nanoparticles are easily accessible due to many supplies from various companies. Also, the processing cost is relatively lower in contrast to the one-step method. Figure 2 demonstrates an example of the two-step method used in fabricating nanofluids [9].
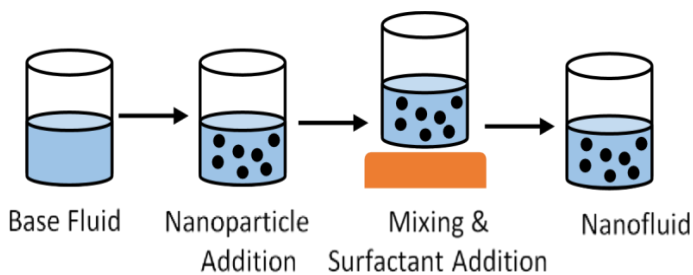
Fig. 2. Two-step metod schematic pricedure

Using the two-step method, one can prepare nanofluids with varying concentrations compared to the one-step method, where the nanofluid concentration is uniform [17]. Various researches claimed that the two-step method is preferable only for fabricating nanofluids with dispersed oxide nanoparticles. It was found to be ineffective for nanofluids with dispersed metallic nanoparticles. The most significant disadvantage of this method is the potential of nanoparticles to form agglomerates compared to the one-step method [18]. It is due to the dominant particle-particle attractive interactions among the nanoparticles during storage, transportation, and handling [3]. However, the two-step method is the most widely used in nanofluid fabrication, even for small or large quantities, due to its cost-effectiveness [18].

4. Enhancement mechanism

The suspension of nanoparticles into the base fluid has observed and resulted in the enhancement and improvement of the heat transfer performance of the storage material [22]. Below there is the list of some enhancement mechanisms of nanoparticles, which are capable of explaining the significant improvement of the thermophysical properties of nanofluids. These mechanisms include the Brownian motion, clustering of nanoparticles, and intermolecular modes of interaction [23].

4.1. Brownian motion

The Brownian motion refers to the erratic motion of particles dispersed into a fluid in which it causes collisions between the particles. It enables direct transportation of heat through solid–solid transport between the particles; thus, the thermal conductivity property of the fluid is expected to augment [23]. Increasing the temperature intensifies the Brownian motion of nanoparticles. The reason behind the enhancement of the thermal conductivity of the fluid is energy transferring due to the collision between the high-temperature and low-temperature particles. Also, the Brownian motion of the particles decreases inversely with increasing bulk viscosity [24].

4.2. Nanoparticle clustering

Nanoparticles always tend to form clusters. This clustering of nanoparticles enables fast heat transportation, especially at relatively long distances due to the formation of high conductivity paths. Figure 3 represents the clustering phenomenon of nanoparticles [24].

Perhaps, solid materials can conduct heat much faster in contrast to liquid materials. Also, the fluid thermal conductivity tends to increase when the cluster size of the nanoparticles grows. However, as nanoparticle volume fraction further escalates, the fluid thermal conductivity having clusters decreases [24].

Aside from the stated enhancement mechanisms above, some of the reasons behind the enhancement of nanofluid thermal properties are that the suspended nanoparticles in the nanofluid provide an extensive surface area that enables plenty of electrons to transfer more heat. Also, the small size of nanoparticles allows them to move freely. Thus, the dispersion of heat is much faster [25].
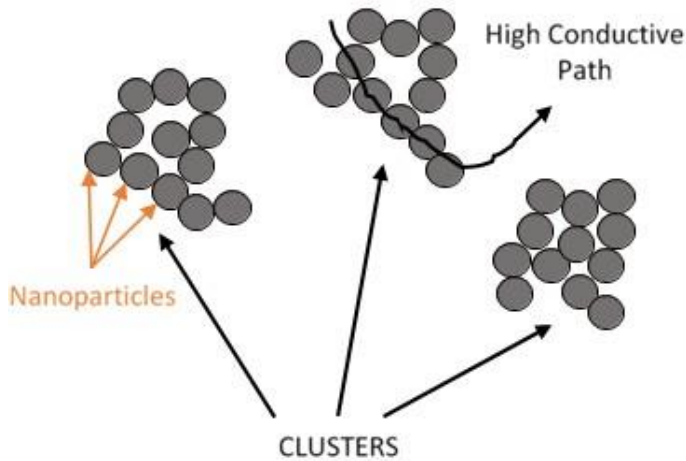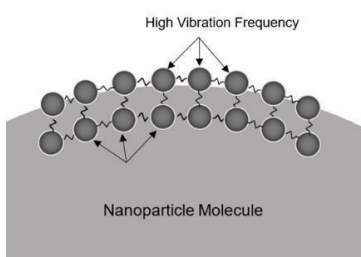
Fig. 3. Clustering of nanoparticles

4.3. Intermolecular modes of interaction

Introducing a highly conductive liquid layer at the liquid and solid particle interface can also enhance the fluid thermal conductivity property. It is due to the ordered atomic structure of the layering liquid compared to that of the bulk liquid. Also, the crystallinity of the solid particles with an ordered structure has better thermal transport properties than that of the liquid; thus, a highly conductive liquid layer at the liquid and solid particle interface can be expected to further increase in the thermal conductivity [23].

The unusual enhancements regarding thermophysical properties of nanofluids due to nanoparticle residence can also be explained by the three intermolecular mechanisms or modes presented below.

### 4.3.1. First mode – Low Vibration Frequency (High Surface Energy)

The nanoparticles specific heat capacity may increase via elevation of energy surface per unit mass. Atoms on the structure surface are barely hindered since there are lesser bonds (Figure 4). Furthermore, these bonds may be represented as elastic springs which vibrate at higher amplitudes and lower frequencies. This would cause the surface energy increase [26].
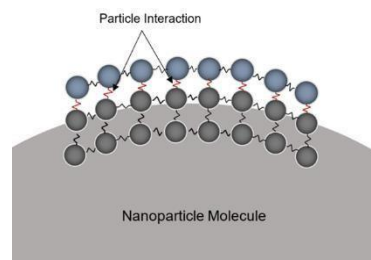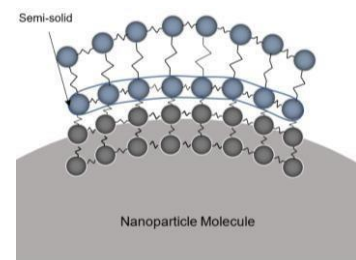
4.3.2. Second mode – Interfacial Interaction (Energy Storage)

The second mode can also be defined as the solid-fluid interaction energy wherein a very high surface area over a mass of nanoparticles would allow the irregular spike of thermal resistance between surrounding fluid particles and the nanoparticles (Figure 5). These elevated levels of thermal resistances act as storages of thermal energy due to the energy vibration between the interfacial molecules and the nanoparticle molecules [26].

4.3.3. Third mode – Higher Mean Free Path (Low Specific Heat)

Fluid layering occurs on the nanoparticles, and these molecules structure themselves in a way where there is a formation of a semi-solid layer (Figure 6).

These layers upon studying contain much greater thermal characteristics than the liquid part and would henceforth allow an increase of the working nanofluid heat capacity. This would require nanoparticles to be made at optimum diameters in order to maximize the fraction of mass and number of adhering molecules, which form the semi-solid layer [26].

5. Results and analysis

Data on different nanofluids as a thermal storage material for CSP practice from various researches and experimentations were gathered along with information on their respective thermophysical properties. Table 1 represents the summary of the collected data on different nanofluids regarding the thermophysical properties: thermal conductivity, density, specific heat capacity, stability, dynamic viscosity, and containment compatibility, and contains the method of preparation.

Fig. 4. Mode 1

Fig. 5. Mode 2

Fig. 6. Mode 3

5.1. Factors influencing nanofluid properties

This research review gathered different combinations of metal nanoparticles and metal oxide nanoparticles with different base fluids from various research articles conducting experimentations to show the enhanced properties of nanofluids that make them an excellent TSM for CSP applications. This research review will also try to present the possible reasons of enhancement of the fluid properties and the factors that affect these enhancements.

5.1.1. Thermal conductivity

All the experimental data gathered agreed that the thermal conductivity of the nanofluids has a proportional effect on the temperature. When the thermal conductivity increases, the temperature tends to grow as well. The temperature affects the Brownian motion, or the random motion, of the nanoparticles when

scattered into the base fluid; thus, it introduces more collisions between the nanoparticles and accelerates heat transfer. Some experimental studies, particularly of stearic acid and n-octadecane, dispersed with TiO_2 nanoparticle [27], showed a sudden and extreme increase in the thermal conductivity close to the melting point of the nanofluid, which makes it desirable for TES systems.

Similarly, all the experimental data gathered agreed that the thermal conductivity of nanofluids tends to increase when the mass percentage of the nanoparticles dispersed into the base fluid also grows. Although some research experiments showed a linear relationship between the thermal conductivity and the mass percentage of the nanoparticles, some research experiments showed a nonlinear relationship and concluded that it is because of the agglomeration of nanoparticles in the base fluid as the mass percentage further increases.

Table 1. Preparation and properties of different nanofluids according to various research articles

Nanoparticles	Type of Nanoparticle	Base Fluid	Enhancement of Properties						References
			Thermal Conductivity	Specific Heat Capacity	Density	Dynamic Viscosity	Stability	Containment Compatibility	
0.3 vol % Cu	Metal	Ethylene Glycol	5 % (10 ºC) 11 % (25 ºC) 33 % (50 ºC)	n/a	n/a	3.5 times (10–30 ºC)	Improved	n/a	[28]
0.5 vol % Cu	Metal		8 % (10 ºC) 16 % (25 ºC) 46 % (50 ºC)			4.2 times (10–30 ºC)			
0.5 wt % TiO₂	Metal Oxide	Palmitic Acid	12.7 %	n/a	n/a	n/a	Slightly Improved	n/a	[29]
1 wt % TiO₂			20.6 %						
3 wt % TiO₂			46.6 %						
5 wt % TiO₂			80 %						
2 wt % TiO₂		Myristic Acid	37.1 %	n/a	n/a	n/a	Improved	n/a	[30]
2 wt % CuO			45.5 %						
2 wt % Al₂O₃			49.6 %						
2 wt % ZnO			50.0 %						
0.05 wt % CuO		Caprylic Acid	36 %	n/a	n/a	n/a	Improved	n/a	[31]
0.05 wt % ZnO			43 %						
0.05 wt % Ag	Metal		52 %						
0.05 wt % graphene oxide (GO)			87 %						
3 wt % TiO₂	Metal Oxide	Stearic Acid	6.97 % (30 ºC) 27.16 % (60 ºC) 17.53 % (70 ºC)	n/a	n/a	n/a	Improved	n/a	[32]
0.5 wt % CuO		Oleic Acid	31.69 %	n/a	n/a	n/a	Improved	n/a	[33]
1 wt % CuO			66.07 %						
1.5 wt % CuO			85.26 %						
2 wt % CuO			98.66 %						
SiO₂		Lauric Acid		n/a	n/a	n/a	Improved	n/a	[34]
0.5 wt % Cu	Metal	Paraffin Wax	14.0 %	n/a	n/a	n/a	Improved	n/a	[35]
1 wt % Cu			23.9 %						
1.5 wt % Cu			42.5 %						

Nanoparticles	Type of Nano-particle	Base Fluid	Enhancement of Properties						Refer-ences
			Thermal Conductivity	Specific Heat Capacity	Density	Dynamic Viscosity	Stability	Containment Compatibility	
2 wt % Cu			46.3 %						
TiO$_2$	Metal Oxide	n-Octadecane	89 % (3 wt %, 28 ºC)	n/a	n/a	1 wt. % TiO$_2$: 10 % 35 ºC) 11 % 45 ºC) 6 % 55 ºC)	n/a	n/a	[27]
0.1 wt % Mg		Li$_2$CO$_3$-Na$_2$CO$_3$-K$_2$CO$_3$ (32.2:33.3:34.5)	19.55 %	n/a	n/a	n/a	Slightly Improved	n/a	[36]
2 wt % Mg			45.11 %						
1 wt % Mg	Metal	NaCl–CaCl$_2$ (52:48)	n/a	3.13 % (250–500 ºC) 1.35 % (580–620 ºC) 3.64 % (680–780 ºC)	n/a	n/a	n/a	n/a	[37]
2 wt % Mg				6.90 % (250–500ºC) 3.41 % (580–620 ºC) 8.49 % (680–780ºC)					
1 wt % SiO$_2$		Li$_2$CO$_3$-K$_2$CO$_3$ (38:62)	37–47 % (150–300 ºC)	5–15 % (150–300 ºC)	n/a	n/a	n/a	Corrosion Rate reduction: [38] At 520 ºC, SS 304 37 % (2 weeks) 59 % (4 weeks) 49 % (6 weeks)	[39]
1 wt % SiO$_2$	Metal Oxide	Hitec XL (49 % NaNO$_3$, 30 % KNO$_3$ and 21 % Ca(NO$_3$)$_2$)	n/a	15–35 % (250–400°C)	n/a	n/a	n/a	n/a	[39]
1 wt % SiO$_2$		BaCl$_2$-NaCl-CaCl$_2$-LiCl (15.9:34.5:29.1 : 20.5)	47 %	12.5–16.3 % (495–555°C)	n/a	n/a	n/a	n/a	[40]
1 wt % SiO$_2$		Solar Salt, KNO$_3$-NaNO$_3$ (60:40)	n/a	11 % (solid) 11.3 % (liquid)	n/a	n/a	n/a	SS 347 [41] 0.024 mm/yr	[42]
1 wt % TiO$_2$				7.9 % (solid) 9.3 % (liquid)				n/a	
1 wt % Al$_2$O$_3$				11 % (solid) 19 % (liquid)				SS 347 [41] 0.019 mm/yr	
0.7wt % Al$_2$O$_3$		MgCl$_2$-KCl-NaCl (51:22:27)	62.59 %	0.22 % (350 ºC) 0 % (450 ºC)	n/a	n/a	Improved	n/a	[43]
0.7wt % CuO			21.58 %	−0.22 % (350 ºC) −0.53 % (450 ºC)					
0.7wt % ZnO			6.47 %	−0.22 % (350 ºC) −0.53 % (450 ºC)					
0.5 wt % Al$_2$O$_3$ 1 wt % Al$_2$O$_3$ 1.5 wt % Al$_2$O$_3$		Mg(NO$_3$)$_2$·6H$_2$O	n/a	n/a	n/a	n/a	Improved	n/a	[44]
1 wt % SiO$_2$		Ca(NO$_3$)$_2$-KNO$_3$-NaNO$_3$LiNO$_3$	n/a	18.6 % (max, aver-age at 350 ºC)	n/a	n/a	n/a	n/a	[45]

Nanoparticles	Type of Nano-particle	Base Fluid	Enhancement of Properties						Refer-ences
			Thermal Conductivity	Specific Heat Capacity	Density	Dynamic Viscosity	Stability	Containment Compatibility	
1 wt % SiO_2		$LiNO_3$-$NaNO_3$-KNO_3 (38:15:47)	n/a	13 %	n/a	n/a	n/a	n/a	[46]
1.0 wt % TiO_2		Lauric Ac-idStearic Acid (70:30)	34.85 %,	n/a	n/a	2.59 %	Improved	n/a	[47]
1.0 wt % ZnO			46.97 %			2.94 %			
1.0 wt % CuO			62.12 %			3.67 %			
1 wt % Al_2O_3		Polyethylene glycol (PEG) 10,000	32 %	n/a	n/a	n/a	Improved	n/a	[48]
2 wt % Al_2O_3			40.55 %						
3 wt % Al_2O_3			45.86 %						
4 wt % Al_2O_3			50.19 %						
5 wt % Al_2O_3			52.90 %						
0.1 wt % Ag	Metal	Polyethylene glycol (PEG) 400	3.9 % (max at 1.1 wt % Ag)	0.9 % (max at 0.1 wt % Ag)	0.16 %	0.011 %	Slightly Improved	n/a	[49]
0.5 wt % Ag					0.94 %	0.057 %			
1.1 wt % Ag					2.2 %	0.13 %			
0.1 vol % TiO_2	Metal Oxide	Erythritol	n/a	26.47 % (solid, aver-age at 67–107 ºC) 3.59 % (liquid, aver-age at 137–167 ºC)	n/a	n/a	Improved	n/a	[50]
0.2 vol % TiO_2				45.06 % (solid, aver-age at 67–107 ºC) 14.41 % (liquid, aver-age at 137–167 ºC)					
0.1 wt % CuO		d-Mannitol ($C4H14O6$)	4.8 %	n/a	n/a	n/a	Improved	n/a	[51]
0.2 wt % CuO			11.2 %						
0.5 wt % CuO			25.2 %						
0.5 wt % Fe	Metal	Magnesium nitrate hexahydrate (MNH)	53 %	n/a	n/a	n/a	n/a	n/a	[52]
0.5 wt % Cu			58 %						
0.005 wt % Au		Therminol VP-1	4.8 %	n/a	n/a	Negligible Enhance-ment	Lessen	n/a	[53]
0.01 wt % Au			5.0 %						
0.05 wt % Au			6.5 %						
1.0 wt %TiO_2	Metal Oxide	Ethylene Gly-col	2.7 %	n/a	n/a	n/a	n/a	n/a	[54]
2.0 wt %TiO_2			7.17 %						
3.0 wt %TiO_2			9.9 %						
4.0 wt %TiO_2			12.7 %						
5.0 wt %TiO_2			16.3 %						
6.0 wt %TiO_2			19.5 %						
(8.75-10) wt % ZnO		Ethylene Glycol	28 %	n/a	n/a	n/a	n/a	n/a	[55]
5.0vol % Sn/SiO_2		HTF Therminol 66 (TH66)	13 %	n/a	n/a	n/a	n/a	n/a	[56]
0.72wt % Ag	Metal	HTO	16.2 %	n/a	n/a	n/a	n/a	n/a	[57]
0.1wt % Graphene Oxide (GO)		Water	18.9 %	n/a	n/a	n/a	n/a	n/a	[58]
0.5 wt % Graphene Oxide (GO)	Metal Oxide		19.9 %						
TiO_2		Diathermic Oil	13.3 %	n/a	n/a	Slightly Increased	Improved	n/a	[59]
0.2 vol % Fe_3O_4		Water	8–17 %	n/a	Slightly Increased	Increased	n/a	n/a	[60]
2.0 vol % Fe_3O_4			25–48 %						
0.2 wt % SiO_2		Water	23.5 %	n/a	n/a	n/a	n/a	n/a	[61]
0.4 wt % CuO		Water	16.7 %	n/a	n/a	n/a	n/a	n/a	[62]
0.005 vol % Al_2O_3		Water	8.1 %	n/a	n/a	n/a	n/a	n/a	[63]
0.10 wt % Cu	Metal	Water	10.7 %	n/a	n/a	n/a	n/a	n/a	[64]

Nanoparticles	Type of Nano-particle	Base Fluid	Enhancement of Properties						Refer-ences
			Thermal Conductivity	Specific Heat Capacity	Density	Dynamic Viscosity	Stability	Containment Compatibility	
1.0 wt % Fe_3O_4	Metal Oxide	Kerosene	34 %	n/a	n/a	n/a	n/a	n/a	[65]
3.0 vol % TiO_2		Water	7.4 %	n/a	n/a	n/a	n/a	n/a	[66]
2.0 vol % $NiFe_2O_4$		Water	17.2 %	n/a	n/a	n/a	n/a	n/a	[67]
1.0 wt % Ag	Metal	Water	11–28 %	n/a	n/a	n/a	Improved	n/a	[68]
3.0 vol % MgO	Metal Oxide	60:40 Water-Ethylene Glycol	30 %	n/a	n/a	n/a	n/a	n/a	[69]
3.0 wt % Al_2O_3	Metal Oxide	Ionic Liquid	7 %	n/a	n/a	n/a	Improved	n/a	[70]

* The majority of nanofluids were prepared using the two-step method except the heat transfer oil (HTO), which is prepared using the one-step method; n/a = no available data.

The dispersion of nanoparticles upon the nanofluid preparation and the morphologies, size, and shape of the nanoparticles can also affect the thermal conductivity of the nanofluid. Based on some experimental research, if the nanoparticles are homogeneously scattered into the base fluid, the heat transfer rate can noticeably improve. In terms of size, it is better to use nanoparticles with smaller sizes because at the surface of the nanoparticles, the heat transfer occurs. Therefore, when the surface area increases, the rate of heat transfer improves. Also, the smaller diameter results in the improvement of the Brownian motion of nanoparticles. In the experimental study of the eutectic mixture of lauric acid and stearic acid dispersed with TiO2, ZnO, and CuO nanoparticles [47], CuO nanoparticles tend to show improvement because of their rod shape compared to TiO2 and ZnO nanoparticles with a spherical shape. Nanoparticles with rod shape tend to have a higher surface area than those of spherical-shape.

Some experimental researches also studied the effect of elapsed time in the thermal conductivity of the nanofluids. On the experimental study of ethylene glycol dispersed with Cu nanoparticles [28], the thermal conductivity was monotonously decreasing as the time increases, until it reached a constant thermal conductivity enhancement of 7.5 % at 15 minutes when the time test ended. It was concluded that thermal conductivity decreases due to the agglomeration of nanoparticles as time passes. Thus, when nanoparticles form agglomerates, the volume ratio of the nanoparticles and the base fluid will decrease, causing the thermal interactions between the nanoparticles to reduce.

Moreover, most experimental results are not similar to theoretical results obtained from the proposed correlations. It was concluded that the discrepancies might be due to the natural Brownian motion, potential of clustering, structure, and surface morphology of the nanofluids, which are not accounted for by theoretical models.

5.1.2. Specific heat capacity

The specific heat capacity of the nanofluids is less studied, compared to the thermal conductivity, in various experimental researches gathered, which focus on using nanofluids in TES systems for CSP application. As we can see from the Table 1, only a few studies considered the specific heat capacity of the nanofluids.

From the data gathered regarding the specific heat capacity, the temperature can affect the specific heat capacity of the nanofluids. Some experimental results showed a proportional relationship between the temperature and the specific heat capacity. However, other experimental results showed an inverse relationship between them.

In terms of the nanoparticle mass percentage, it can also cause changes in the specific heat capacity of the nanofluids. Some experimental researches showed a minimal decrease in the specific heat capacity when increasing the mass percentage of nanoparticles. In the experimental study of polyethylene glycol 400 dispersed with the different mass percentage of Ag nanoparticles [49], the specific heat capacity was 0.9 % at 0.1 wt % of the Ag nanoparticles. However, as the mass percentage of the nanoparticles increases, a slight reduction of the specific heat capacity is noticed, but insignificant changes. On the contrary, other studies showed that the specific heat capacity increases as the mass concentrations of nanoparticles grow. In the experimental study of NaCl–CaCl2 (52:48) dispersed with 1 and 2 wt % Mg [37], the specific heat capacity of the solid, solid-liquid, and liquid

state regions increases as the nanoparticle concentration grows.

The nanofluid preparation also affects its specific heat capacity. The ultrasonication during the preparation is a critical step since the uniformity of the dispersion of nanoparticles highly depends on it. If the nanoparticles do not undergo the ultrasonication, there will be an adverse effect on the specific heat capacity; thus, the specific heat capacity of the nanofluid will decrease due to the agglomeration of nanoparticles.

All the experimental researches agreed that the unusual increase of the specific heat capacity of the nanofluids is chiefly because of the nanostructures formed at the solid-liquid interface. As the nanoparticle is homogeneously dispersed in the base fluid, for example, molten salt, the salt compounds within the mixture will tend to be separated because there are different electrostatic interactions between the nanoparticles and the salt compounds. The salt compound, which is separated, will crystallize at the surface of the nanoparticles and further form an interconnected nanostructure. As a result, the surface atom is greater than the interior atoms; thus, it causes the specific heat capacity to improve.

Moreover, most experimental results are not similar to theoretical ones obtained from the proposed correlations. It was concluded that the discrepancies might be because of the formation of the interconnected nanostructure within the nanofluid, which is not considered by the proposed theoretical models.

5.1.3. Density

As it is seen from Table 1, the density of the nanofluids is unconsidered by most researchers regarding the thermophysical properties of nanofluids. From the experimental researches gathered, only two studies have considered the density of the nanofluids. TES for CSP applications, the density property of the TSM will be used as a basis regarding the equipment sizing.

Density is not as much focused as compared to the thermal conductivity since this property is mainly related to the specific heat capacity, which is defined as the amount of heat a material can hold. Since specific heat capacity does not enhance the rate, then it is at most times considered as insignificant for studying.

In the study of polyethylene glycol 400 dispersed with Ag nanoparticles [49], the nanofluid density was found to increase proportionally as the mass percentage of nanoparticles also increases. It is because the nanoparticles itself tends to have high density compared to fluids. Also, the density of the nanofluids does not dependent on the temperature; thus, density is unaffected by any changes in the temperature.

Density is the ratio of mass over the volume. As the weight of the nanoparticles submerged in the base fluid increases, the amount of mass within the substance also grows. Thus, as there is an increase in mass, the density will increase as well.

5.1.4. Dynamic viscosity

Similar to the density, dynamic viscosity is not also focused on much in the experimental researches on the property enhancements of the nanofluids as a desirable TSM for CSP applications. However, based on the gathered data, there is more data on the dynamic viscosity than on the density. The dynamic viscosity of the TSM will be used in TES systems for CSP applications as a basis for the pumping power penalty.

The dynamic viscosity of a nanofluid is concerned when it is ready to be used in a TES system. As it was mentioned in this study, it is used as a basis for the pumping power penalty that the system would suffer during charging/discharging operations. Since most studies conduct characterization only of the thermal conductivity, without thorough simulation under CSP application, then this property is not essential to be analyzed.

The surfactant added during the preparation can also cause changes in the dynamic viscosity of the nanofluids. In the study of ethylene glycol dispersed with Cu nanoparticles [36], the addition of polyvinylpyrrolidone (PVP) surfactants improved the dynamic viscosity of the nanofluid by three, almost four, times when compared to the pure ethylene glycol.

All the experimental results gathered agreed that the temperature has an inverse effect on the dynamic viscosity; thus, increasing temperature causes decrease in dynamic viscosity. It was concluded that the inverse relationship between the temperature and dynamic viscosity was due to a decrease in the intermolecular forces of the nanoparticles, causing the reduction of the dynamic viscosity. Also, as the dynamic viscosity of the nanofluid diminishes, the Brownian motion of the nanoparticles rises.

Moreover, the shape of the nanoparticles was reported to influence the dynamic viscosity of the nanofluids. In the experimental research of the eutectic mixture of lauric acid and stearic acid dispersed with TiO_2, ZnO, and CuO nanoparticles [47], all types

of nanofluids have shown improvement on the dynamic viscosity. However, the CuO nanoparticles acquire the highest enhancement. It was concluded that it was due to its rod shape compared to the other two nanoparticles with the spherical shape.

The nanofluid dynamic viscosity is interpreted as its resistance to flow. It is synonymous with the density that as the number of solutes increases, the fluid becomes much more concentrated. The particles would have lesser spaces between each other and would, as a result, be less flowing. It can be observed from the studies that as the nanoparticle weight increases, the dynamic viscosity would also increase.

5.1.5. Stability

Throughout the studies, the stability of the nanofluids has undergone short-term analysis to observe whether there might be degradation or agglomeration. However, more data is required to determine the stability of materials for long-term usage.

The measurement of the stability of the nanofluids was based on weight loss, which is related to the degradation of the prepared nanofluids as a function of temperature. The experimental results showed that as the temperature rises, the weight loss also rises. At the beginning of the weight loss, it was concluded that it was due to water loss. As the temperature further increases, it will come to a time that only the nanoparticles will leave. It was noticed that the weight loss of nanofluids happens at much hotter temperatures in comparison to the pure base fluid. Therefore, the addition of nanoparticles delays the decomposition of the nanofluids. According to some experimental results, it is because of the improvement of the physical bonding interactions between the base fluid molecules due to the addition of nanoparticles, resulting in the nanofluid being heat resistant.

Thermal nanofluids stability is also influenced by the uniform nanoparticle distribution into the base fluid upon preparation, and the nanoparticles size. Suppose the nanoparticles are properly incorporated into the base fluid, and the nanoparticle size is ultimately small. In that case, the agglomeration will be prevented, which also prevents the nanoparticles from sedimentation, resulting from the increase in the nanofluid thermal stability.

The mass percentage of the dispersed nanoparticles affects the nanofluid stability. All the experimental results agreed that as nanoparticle mass percentage rises, the nanofluid stability decreases because, at the higher mass percentage of nanoparticles

dispersed into the nanofluid, the possibility of agglomeration is more likely to occur.

Moreover, the addition of surfactants upon nanofluid preparation and type of surfactant used can also influence the nanofluid stability. In general, all results from various experiments showed that the addition of surfactants, usually polyvinylpyrrolidone (PVP), enhances the thermal stability of the nanofluids. It was concluded that it was because the surfactants tend to stay at the surface of the nanoparticles in acidic conditions. Thus, the electrostatic repulsions between the nanoparticles dominate the Van de Waals interaction, preventing the nanoparticles from agglomerating; thus, making the nanofluid stable. However, not all types of surfactants have a positive effect on stability. In the experimental research on the sugar alcohol erythritol dispersed with TiO_2 nanoparticles [50], different types of surfactants are used to test their effect on nanofluid stability. The results showed that out of the six surfactants used, only the triethanolamine (TEA) and oleic acid (OA) were effective for the prepared erythritol-TiO_2 nanofluid.

5.1.6. Containment compatibility

The data on containment compatibility in terms of the corrosion of nanofluids are absent in this research review. Thus, this research review attempts to do further research. However, the data on the corrosion of nanofluids is minimal, unlike other nanofluid properties.

Experimental study of corrosion of the eutectic carbonates mixture dispersed with one weight percent of SiO_2 nanoparticles in the stainless steel 304 containers at 520 °C [65] shows that the prepared nanofluids tend to be less corrosive than the pure eutectic carbonates mixture. The testing corrosion periods are 2, 4, and 6 weeks, and the corrosion rate reduces for about 37, 59, and 49 %, respectively. It was concluded that the possible cause for corrosion rate reduction was the passive layer formed by the nanoparticles and the carbonate salt complex, which prevents the nanofluid further corrosion. Another possible cause is that the nanoparticles act as a physical barrier by migrating at the container walls that causes a decrease in corrosion rate.

The experimental study of the corrosion of the solar salt dispersed with SiO_2 and Al_2O_3 nanoparticles [68] shows that the addition of nanoparticles is unable to cause corrosion rate reductions of the prepared nanofluid. It was concluded that maybe due to the

corrosion rate measured at static conditions. Since nanoparticles are solid in the nanofluid, it is better to measure corrosion at dynamic conditions. These nanoparticles have great potential to cause corrosion in the pipelines and tanks used by CSP plants.

5.1.7. Enhancement of other properties

In thermal storage systems for applications in CSP, the most critical properties of a TSM include and are not limited to density, specific heat capacity, stability, thermal conductivity, dynamic viscosity, and containment compatibility. There are also other properties enhanced due to the dispersion of nanoparticles.

These factors were studied as well, but they are not crucial during the characterization of the nanofluid properties. Thus it may be derived that there is a lack of data on these variables.

5.1.7.1. Conductive heat transfer

Conductive heat transfer is related to the time savings or the time reduction to change the TSM phase. Experimental data showed that nanoparticle addition increased the percent time savings of the nanofluids rather than having the pure base fluid alone. Also, it was concluded that the convective transfer of heat accelerated due to the developed conduction heat transfer as the nanoparticles undergo dispersion as it enters into the base fluid; thus, the heat transfer rate is higher. Therefore, nanofluids are more desirable to use TSM since the time savings are much higher than conventional fluids.

Also, the type of nanoparticles used has a different impact on conductive heat transfer of nanofluids. In the experimental study of caprylic acid dispersed with CuO, ZnO, Ag, and graphene oxide nanoparticles with an equal mass percentage of 0.5 [31], the time savings obtained to complete the melting of the nanofluid were 5.43, 15.51, 26.85, 33.51 %, respectively. The time savings obtained to complete the nanofluid solidification were 5.66, 12.96, 20.43, 34.47 %, respectively.

5.1.7.2. Latent heat

The latent heat property is used to identify the thermal energy storage capacity of a TSM. In TES systems, higher values of latent heat are most desirable.

The nanoparticles mass percentage has an inverse relationship with the capacity of latent heat of the nanofluid. Also, as the mass percentage of nanoparticles dispersed into the base fluid increases, the latent heat decreases. One of the reasons behind it is that the mass ratio of the pure base fluid decreases. Also, the nanoparticles and the base fluid have different specific heat capacities. When mixed, the latent heat of the nanofluid is affected; thus, it decreases.

Most experimental outcomes showed that latent heats of nanofluids are much greater than that of the conventional fluid. However, there are also some experimental researches that obtained different results. In the experimental study of the salt $MgCl_2$–KCl–NaC dispersed with metal oxide nanoparticles [43], the latent heats of the prepared nanofluids decrease by about 2.4 to 7.6 % in contrast to the latent heats in the base fluid.

5.1.7.3. Thermal reliability

The thermal reliability is used to identify the average life cycle of the nanofluids by subjecting it to cyclic thermal operations. Experimental results and data depicted that latent heat or thermal storage capacity of a TSM has a lesser percent reduction for nanofluids than for the conventional fluids. In the experimental study of palmitic acid dispersed with TiO_2 nanoparticles [29], the different varieties of the latent heat of fusion of the nanofluids at 100th, 500th, 1000th, and 1500th cycles were –2.0, –0.26, –1.42, and –2.54 % in comparison to those of the pure palmitic acid. It was concluded that the prepared nanofluid has an average life cycle of five years to be effectively used in systems of energy storage, both for industrial and even domestic applications.

The type of nanoparticles used causes varying outcomes on the nanofluid thermal reliability. In the experimental study of stearic and lauric acid mixture dispersed with TiO_2, ZnO, and CuO nanoparticles with similar mass percentages of 0.1 [47], during nanofluid melting, the latent heat percent reductions were 1.67, 1.72, and 1.61 %, respectively. During the nanofluid solidification, the latent heat percent reductions were 1.54, 1.63, and 1.48 %, respectively. The obtained percent reductions of the latent heats from the processes of phase change of the nanofluids were lesser in contrast to those of the pure base fluid at 5000 cycles. It was concluded that the prepared nanofluids have an average life cycle of thirteen to fourteen years.

5.1.7.4. Thermal diffusivity

The thermal diffusivity of the nanofluids is used to measure the heat transfer rate of a thermal storage fluid from the warmer side to the lower cooler side.

Addition of nanoparticles has also caused the enhancement of the thermal diffusivity along with the enhancement of other properties.

The mass percentage of the nanofluids can affect the thermal diffusivity of the nanofluid. The experimental results agreed that when the nanoparticles mass percentage increases, the nanofluid thermal diffusivity also increases. A conclusion points out that the heat transfer from the warm side to the cool side was fast within the nanofluid.

Moreover, the temperature slightly affects the thermal diffusivity. The results from experiments illustrated that the thermal diffusivity decreases linearly when the temperature rises.

5.2. Evaluation

This paper evaluates the data on nanofluids available in different research articles from various journals investigating the properties of nanofluids from preparation up to experimentation. These articles have aimed to provide the readers with a background on thermal energy storage fluids and the significant role of these materials in enhancing the overall efficiency of heat to energy conversion during operating hours. This paper also illustrates the potential of using nanofluids over normal base fluids, thus giving future researchers a guide on different key factors to be studied during the experimentation of novel nanofluids.

However, the results obtained from the gathered data provided us only a brief overview of different factors, such as the enhancement of thermal conductivity or stability. There are still many limitations to be considered based on obtained data and improvements to be made before the complete integration of these materials for TES use.

5.2.1. Inconsistent and insufficient material characterization

Nanoparticle and nanofluid characterization methods are either lacking in uniformity or give incomplete information. Not all studies have the same method of examining the particle size or shape of the material.

5.2.2. Narrow scope of research data

The scope of the research was quite narrow. Most data presented in this paper were from articles that focused mainly on a few fundamental properties like the thermal conductivity or stability of the nanofluid. The analysis presented in this paper showed that there are other factors to be considered, such as fluid viscosity or specific heat capacity. These are also variables that contribute to the properties of the nanofluid and are used as a basis for a fluid to be feasible to use as TSM.

5.2.3. Lack of data and economic factors

Costs for material acquisition and preparation such as nanoparticle importation, dispersion setup, and other materials for preparing the nanofluid, have not been considered in various articles.

5.2.4. No consideration of material longevity

Long-term effects of the use of nanofluids were absent in different papers. The use of these fluids is in line with the previous paragraph, where it should be, at the very least, economical. Moreover, one characteristic to be considered is how long would the fluid lasts before it is needed to be replaced. Moreover, the containment materials contribute to the cost since there might be long-term corrosion or degradation since these materials operate at high temperatures.

5.2.5. Nanofluid weight limit

The studies regarding the maximum amount of weight of nanoparticles dispersed in the nanofluid are still lacking. However, most studies show that the rise of the mass percentage of the nanoparticles would cause an improvement in the thermal conductivity of the nanofluid. However, there would also be consequences on the other properties such as density or viscosity.

6. Conclusion and recommendations

This chapter presents the summary of the overall findings, the information on nanoparticle with the highest yield, and the recommendations.

6.1. Nanoparticle with the highest yield

Based on the gathered data, the most used category of nanoparticles is metal oxides. Table 2 represents some of the nanofluids dispersed with the commonly used metal oxide nanoparticles with equal mass percentages. Table 2 will be used as a basis for which metal oxide nanoparticle has a better yield in thermal conductivity enhancement.

Table 2. Nanofluids with metal oxide nanoparticles

Nanoparticles	Base fluid	Thermal conductivity (% enhancements)
0.7 wt % Al_2O_3	MgCl$_2$–KCl–NaCl (51:22:27)	62.59
0.7 wt % CuO		21.58
0.7 wt % ZnO		6.47
1.0 wt % TiO_2	Lauric acid–Stearic acid (70:30)	34.85
1.0 wt % ZnO		46.97
1.0 wt % CuO		62.12
2 wt % TiO_2	Myristic acid	37.1
2 wt % CuO		45.5
2 wt % Al_2O_3		49.6
2 wt % ZnO		50.0

As Table 2 shows, Al_2O_3 is the metal oxide nanoparticle with the highest yield. Although in the myristic acid, ZnO showed the highest enhancement, and the Al_2O_3 comes next. Nevertheless, the difference in the enhancement of ZnO and Al_2O_3 is minimal; thus, negligible, or considered equal. The nanofluids with the base fluids of MgCl$_2$–KCl–NaCl and lauric acid– stearic acid showed lesser enhancements in terms of the ZnO nanoparticles. Therefore, among the metal oxide nanoparticles, nanofluids with Al_2O_3 nanoparticles are more promising to use as TSM for CSP applications, specifically in TES systems, as they showed better improvements on the properties of the nanofluids.

6.2. Conclusion

This research review has been able to satisfy its two objectives: to gather a comprehensive set of data on experiments conducted in nanofluid applications from different articles and to relate the favorable design of the CSP on the commonly TSMs alongside the properties of transpiring nanofluids.

This research review has been able to gather, though not comprehensive, several sets of data from different experimental research articles regarding the physical and thermophysical properties of the nanofluids as a prospect TSM, specifically for the applications in CSP.

As this research review relates to the favorable design characteristic of the CSP between the commonly used TSM and nanofluids, there are favorable enhancements observed from the data gathered throughout different studies. As compared with the base fluid alone, nanoparticle dispersed fluids provided much

more favorable thermophysical properties, particularly the thermal conductivity of the nanofluids, which is of primary interest for almost all conducted researches. In addition, nanofluids portrayed characteristics that allows them to be used for TES, which strengthens the claims made in this paper.

6.3. Recommendations

Even with the challenges faced in the pursuit of the use of nanofluids, it can be deduced that this material has the capacity to improve the efficiency of the use of thermal energy under the solar power sector of energy production. This could not only improve concentrated solar power operations but also cut back on the use of fossil fuels that pollute the planet. The research of nanofluids has been a pioneering segment in the scientific world since it has a broad scope of application.

Further depth on the study of nanofluids may increase the rate of development as it could shorten the period in which these storage media may be fully realized. It is worth noting that nanofluids have gathered an astounding amount of attention over the past decades since numerous researches have already been conducted in this area of study. Moreover, this/they may pave the path towards the sole use of green energy alone. Table 3 show overall findings by the authors.

Below there are a few suggestions that may be observed for future research and development of nanofluids:

Uniform material characterization methods. To prevent results from being incomparable due to different characterization methods, it would be best that for future researches, all materials would undergo the same process of characterization so that the data obtained will be valid upon the comparison.

Tests for other key properties. Most researches have only the data regarding the changes in the thermal conductivity while only stating observations were made on the physical behavior of other properties such as density and viscosity. It would be much better if all the other properties were also studied. There might be dramatic changes in other variables.

Inclusion of economic factors. Since there is a lack of data regarding the costs of material acquisition, preparation, etcetera, it would be better to present the data regarding the costs that would benefit future research and those companies looking into articles that study materials with great potential. Companies do this research to have an initial idea of the

costs of implementing thermal storage, where there should be a reduction in expenses in the long run compared to fossil fuels. It would provide CSP plants with a valid reason for the implementation of TES to maximize the energy that would be absorbed from the sun while reducing uneconomical expenses such as using fossil fuel during instances where solar energy is insufficient.

Material longevity. Since there have been no tests on the plausible negative effects of nanofluids for more extended periods, a proposition to this issue would be for researchers to conduct long-term experiments applying commonly used materials in storage systems. It could provide insight if the usage of nanofluids were either practical or disadvantageous.

Table 3. Summary of the overall findings

Properties of nanofluids	Performance parameter	Desired characteris-tic	Factors affecting nanofluid properties	Conditions	Effect on nanofluid properties	Reason/Limitation
Thermal conductivity	Heat exchanger performance–heat transfer rate (between two materials)	High	Temperature	High	High	Improved Brownian motion
			Mass percentage of nanoparticles	High	High	More heat will be transferred between the nanoparticles
			Preparation of nanofluids	Well prepared	High	No nanoparticle agglomeration
			Characterization of nanoparticles	Small size and Rod-shaped	High	Some studies claimed that the desirable nanoparticle size is around 20 nm. The rod-shape size has a high surface area
			Elapsed time	High	Low	Nanoparticle agglomeration
Specific heat capacity	Energy storage capacity	High	Temperature	Needs further research due to inconsistent results		
			Mass percentage of nanoparticles	Needs further research due to inconsistent results		
			Preparation of the nanofluids	Well prepared	High	No nanoparticle agglomeration
Density	Equipment sizing	Low	Mass percentage of nanoparticles	High	High	Nanoparticles adds mass on the nanofluid
Dynamic viscosity	Pumping power penalty	Low	Addition of surfactants	n/a	Low	Nanoparticles are homogenously scattered into the base fluid
			Temperature	High	Low	The interactions among the particles within the nanofluid are lessened
Stability	Material degradation	High	Temperature	High	Low	High temperature causes more weight loss
			Characterization of nanoparticles	Well prepared and small size	High	No nanoparticle agglomeration
			Mass percentage of nanoparticles	High	Low	Some studies claimed that the desirable mass percentage of the nanoparticles is limited at 5 wt % to prevent agglomeration
			Addition of surfactants	n/a	High	Surfactants allow the nanoparticles to be homogeneously dispersed into the nanofluid
Corrosion	Containment compatibility	Low	Needs further research due to lack in data			
Conductive heat transfer	Time saving	High	Mass percentage of nanoparticles	High	High	The addition of nanoparticles causes time savings to increase

Latent heat	Absorbed/released energy (during material phase change)	High	Mass percentage of nanoparticles	High	Low	The mass ratio of the base fluid decreases
Thermal reliability	Material average life cycle	High	Thermal cyclic operations	High	Low	Latent heat tends to decrease
Thermal diffusivity	Heat transfer rate (high to low temperature within a material)	High	Mass percentage of nanoparticles	High	High	There is faster heat transfer from top to bottom within the nanofluid.

*n/a = not applicable.

Additional studies on nanoparticle weight. The behaviour of the critical thermophysical properties of the nanofluid with varying nanoparticle weights should be further explored. Several studies have proclaimed that 5 wt % of nanoparticle weight is the best for thermal energy applications. However, as other research increased the nanoparticle weight, it would also yield more favourable results. It would be advisable to conduct further studies on the effects of having higher nanoparticle weight to see if it would be either advantageous or disadvantageous.

Nomenclature

Symbols
wt.   by weight (%)
vol.   by volume (%)

Abbreviations
CSP   Concentrated Solar Power
TSM   Thermal Storage Material
TES   Thermal Energy Storage

Chemical Formula
Cu   Copper

Ag   Silver
Mg   Magnesium
Fe   Iron
SiO_2 Silicon dioxide
TiO_2 Titanium dioxide
CuO   Copper oxide
ZrO_2 Zirconium dioxide
ZnO   Zinc oxide
Al_2O_3 Aluminum oxide
GO   Graphene oxide
Fe_3O_4 Iron oxide
MgO   Magnesium oxide

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