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Nanofluids and engineering applications: A review

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Abstract

With the development of technology, the search for advanced materials has accelerated. Nanomaterials have emerged as an important material group in this search and have found a place for themselves in many different areas. Nanofluids, which are formed by dispersing nanoparticles in basic liquids such as water, ethylene glycol, or oils, have emerged as a very innovative method in the applications of nanoparticles. They have also found a wide range of applications. The improved thermophysical properties of nanofluids have made this research area important in engineering. Nanofluids have gained a unique area, especially in cooling and lubrication systems due to their higher thermal conductivity, viscosity, and convective heat transfer properties compared to traditional liquids. Nanofluids also hold promises in solar energy systems, defense industry systems, nuclear plants, biomedical applications, automotive, and aviation industries where efficient cooling is important. It has also been shown that the use of nanofluids in processing and lubrication processes increases product quality and minimizes wear. Despite these benefits, problems such as stability, cost, and long-term performance in nanofluids continue. These challenges continue to be investigated with a focus on optimizing nanoparticle concentration, developing dispersion methods, and analyzing the environmental impact of nanofluids. Computational and experimental studies will help to understand the flow behavior and heat transfer processes of nanofluids under different operating conditions. The aim of this paper is to review existing nanofluid studies. It provides an overview of the current developments and applications in the field of engineering, focusing on their functions in heat transfer, energy systems and industrial processes.

Keywords: Nanofluids; Heat transfer; Nanofluids Applications; Engineering Applications.

1.Introduction

In the scientific discipline of nanotechnology, materials are manipulated at the atomic and molecular levels to produce novel and practical materials [1]. Compared to macroscopic materials, nanometer-sized materials are more physical, chemical, and biological due to their high surface area-to-volume ratio [2]. Because of these characteristics, nanotechnology is essential in many different domains, such as materials science, medicine, electronics, energy, nanofluids, and the environment [2–13,13–18] Nanofluids are an important application area for nanotechnology [19]. Nanofluids are created by combining liquids with particles as tiny as nanometres [20]. In fields like heat transfer and energy management, innovative solutions are provided by modifying the stability, viscosity, and thermal conductivity of nanofluids [21]. By altering the size, surface characteristics, and chemical makeup of the particles, nanotechnology creates nanofluids with a uniform and stable dispersion in the liquid [22]. Important heat transfer issues may be resolved as a result of this process, and designs can be linked in accordance with widely accepted engineering standards [23]. This situation is also very valuable in the uninterrupted flow of energy. This is important in the most ideal distribution of energy that increases the quality of life [24]. These properties make it possible to use nanofluids more effectively in engine cooling systems, heat exchangers, solar collectors, nuclear reactors, and the military sector [25,26]. In recent years, nanofluids have become increasingly important in engineering applications. It is possible to take a closer look at the basic components of this technology and different aspects of its application areas. In the following section, nanofluid application areas, experimental studies, economic and environmental impacts in this field, and prospects are discussed.

2. Nanofluids and Fundamentals

Advances in science have now reached a point where dimensions below the micrometer range are now possible, thus facilitating significant progress in overcoming problems related to size and surface area [27]. In this context, nanotechnology science has become a central focus, playing a pivotal role in numerous fields including energy, medicine, mechanical engineering, and civil engineering [28–32]. Nanoscience has effectively integrated diverse scientific disciplines, resulting in comprehensive breakthroughs, fundamental scientific discoveries, and technological advancements [33]. The benefits expected from mastery of this technology are frequently significantly greater than those achieved by humans to date [34]. The manipulation of matter at the nanometer scale, and the exploitation of new properties and phenomena created at this scale, enable the efficient production and use of materials [35]. A salient feature of this technology is its capacity to manipulate matter at the molecular and atomic scale to create suitable structures, thereby endowing these systems with advanced and novel physical, chemical, and biological capabilities [36]. A distinguishing characteristic of this technology is the presence of fundamental components that influence the properties of the system. For instance, the high surface-to-volume ratio of nanoparticles is a hallmark of this technology [37–39]. The exploitation of this feature has the potential to effect substantial alterations in the efficiency of chemical reactions and the physical properties of materials, thereby engendering enhancements in the thermal and chemical characteristics of the material [40,41] It is at this juncture that nanofluids assume significance.

Nanofluids are defined as fluids with superior thermal and physical properties created by dispersing nanometre-sized (1-100 nm) solid particles in a conventional base fluid [42]. This technique has a wide range of applications in mechanical engineering, especially in hydraulic fluids, nuclear plants, defence engineering, solar cell technologies, and heat transfer systems [19,43,44]. The concept of nanofluid was first proposed in the early 1990s by Stephen U. S. Choi of Argonne National Laboratory [43]. According to Choi's research, the dispersion of nanometre-sized particles in a base fluid can lead to a significant increase in heat conduction capacity [44]. Nanofluids, which are mixtures of a base liquid with small amounts of metal or metal oxide nanoparticles, are used in many areas of human life, such as electronics, medicine, energy, machine technologies, and chemical devices [45]. The ability to control transport processes such as drag conveying systems and the improvement of heat and mass transfer due to the low concentration of nano-sized particles are the main reasons for the wide range of applications of nanofluids [46]. The properties of nanofluids offer several advantages, including improved heat transfer performance, increased energy efficiency, and long system life [47]. The properties of nanofluids depend fundamentally on the type of nanoparticle, the base fluid, and the dispersion processes used [48]. Material selection for nanofluids is determined by parameters including good thermal conductivity, chemical stability, low density, and biocompatibility if used in a biomedical system, but usually also requires parameters such as, but not limited to, cost, degradability, etc. [49]. Metals such as copper and silver are particularly noteworthy for their strong thermal conductivity; however, metal oxides, including aluminium oxide (AlO) and titanium dioxide (TiO_2), are also frequently selected for their chemical stability. Carbon nanotubes (especially SWCNT) and graphene are extensively utilized in various applications due to their low density and exceptional thermal characteristics [50]. The composition of nanoparticles can vary with examples such as metal oxides (Al_2O_3, TiO_2, CuO), pure metals (Cu, Ag, etc.), and carbon-based materials (graphene, carbon nanotubes(MWCNT and SWCNT) [51]. The most salient feature of nanofluids is that their thermal conductivity is significantly higher than that of traditional liquids. The presence of nanoparticles in the liquid accelerates the transfer of energy and improves convective and conduction-based heat transfer mechanisms [52]. Furthermore, nanofluids can exhibit reduced viscosity, enabling more efficient fluid pumping [53]. In the studies, the addition of solid particles to the base liquids causes changes in the density, specific heat, viscosity, and thermal conductivity of nanofluids. These factors should be considered in the planning stage to ensure the optimum thermal performance of nanofluids. At extremely low particle loadings, the base liquid exerts a dominant effect on the density and specific heat capacity and receives minimal effect from solid particles [54,55]. The specific heat capacity of copper (390 kJ/kgK) is considerably less than the specific heat capacity of water (4184 kJ/kgK - 20 °C). As can be clearly seen, the specific heat of nanofluids decreases as the filling ratio increases. If 10% copper nanoparticles are added to a base liquid (water) by volume, the specific heat decreases to approximately 2300 kJ/kgK, which inhibits the heat transfer capacity of the liquid. The basis of the studies was to increase the thermal conductivity while minimizing the percentage of nanomaterials [55]. One of the most important issues for nanomaterials is the liquids in which a particle is suspended.

Also, improving the stability of nanoparticles is essential for enhancing nanofluid performance and avoiding sedimentation. Selecting the right dispersion techniques for various applications helps to maintain the stability of nanomaterials over time in addition to ensuring their uniform distribution [56]. The fundamental dispersion techniques employed here include ultrasonic dispersion, magnetic stirring, mechanical stirring, pH control, and surfactant use [57]. By high-frequency sound waves, the ultrasonic dispersion process isolates nanoparticles from one another and guarantees their uniform dispersion throughout the liquid. When used to high-density nanofluids, this technique works exceptionally well. Simpler techniques for low-viscosity liquids include mechanical and magnetic churning, however they might not totally stop aggregation. By adjusting the pH and adding surfactants, the nanoparticles' surface charge may be changed [58]. By changing the surface charge of nanoparticles using pH adjustment and surfactants, they can be repelled from each other, which reduces sedimentation and increases stability. The volume fraction of nanomaterials is an important factor that directly affects the viscosity and heat transfer properties of the system. Low volume fractions (usually between 0.1% and 1%) will allow particles to remain stable for longer periods, while high volume fractions (5% and above) may increase the tendency to sediment. The dispersion technique used determines how well the nanoparticles are dispersed in the liquid, and if the appropriate method is not selected, particles may coalesce and sediment [59]. Another crucial factor is dispersion duration, while longer times may be needed for magnetic or mechanical stirring. Excessive dispersion time, however, can also result in excessive particle fragmentation, which compromises stability [60].

However, various base fluids can be used. Water, ethylene glycol, and hydraulic oils are among the most used base fluids. Proper distribution of the nanomaterial in these fluids is important. For this distribution, dispersion techniques play an important role in ensuring the homogeneous distribution of particles. For this purpose, ultrasonic mixers, dispersants, and electrostatic forces are used. At the same time, stability is another of the most critical factors affecting nanofluid performance over time [61].

Since the introduction of nanofluids in about 1990, researchers have conducted meticulous studies on the properties and potential applications of these innovative materials. A distinctive feature of nanofluids is their unique heat transfer properties compared to conventional coolants; they are particularly notable for convective heat transfer and thermal conductivity [62]. As noted, the thermal and mechanical behaviour of the base fluid is improved with nanofluids [63]. This improvement significantly contributes to the extension of system life and reduction of failure rates, especially in industrial equipment exposed to high temperatures [64] [65]. Due to these properties, nanofluids have begun to gain a wide range of applications in industrial products. These include beyond hydraulics, nanofluids find applications in various mechanical engineering contexts [66]. In the field of solar energy systems, nanofluids have been used to increase the heat transfer efficiency of solar collectors [67]. The incorporation of nanoparticles with extremely high thermal conductivity, such as graphene and carbon nanotubes, has been shown to provide significant advantages in solar energy applications [67]. For example, graphene- water-based nanofluids have been shown to exhibit approximately 20% higher heat transfer capacity compared to conventional water-based fluids [68]. It is also used in surfactant materials to increase stability in nanofluids. While the choice of surfactant depends on the particle type and the base fluid, its amount depends on the nanofluid ratio. In the literature, the surfactants typically used in the preparation of CuO-water nanofluids are usually sodium dodecyl sulfate (SDS), Cetyltrimethylammonium bromide (CTAB), polyvinyl alcohol (PVA), polyvinyl propylene (PVP), oxalic acid (OA), etc. However, as the nanoparticle ratio used in the medium increases, surfactant is especially used to overcome the sedimentation problem [69].

This improvement allows energy systems to capture more energy in less time. Nanofluids are widely used in cooling systems, engines, engine radiators, cooling applications for electronic devices, and cooling systems for nuclear reactors [70]. These applications can be highlighted as unique behaviours in mechanical engineering component studies [71]. Studies have shown that TiO_2-doped nano coolants are 29.5% more effective than typical water-based coolants in the final cooling of electronic devices [72]. In the aerospace sector, nanofluids facilitate the development of compact and energy-efficient cooling systems and are used in applications such as military equipment and high-power laser diodes. In electronics applications, particularly microchip cooling, nanofluids have the potential to improve convective heat transfer. Studies have shown that nanofluids provide an effective cooling technology by increasing thermal conductivity in microchannel heat sinks [73,74]. There is a lot of promise for industrial cooling and energy conservation with nanofluids. For example, the incorporation of nanofluids into industrial cooling systems has been demonstrated to lead to significant savings in energy usage, which in turn helps to lower emissions [75].

Heating buildings and lowering pollution levels are two further uses for nanofluids. Heat exchangers using nanofluids can improve energy efficiency by lowering volumetric and mass flow rates, according to a study done in cold climes. The study's conclusions suggested that switching to smaller heating systems might save expenses while improving environmental sustainability [19]. The basic fluid's ability to transfer heat is improved by the suspended metallic nanoparticles that make up nanofluids. When the concentration of these particles is higher, the nanofluid shows improved heat transfer characteristics [76,77]. To determine how this phenomena works, experiments were carried out using copper oxide, aluminium oxide, and silicon dioxide nanofluids in a mixture of ethylene glycol and water [78–80]. The calculations were cantered on finned-tube heat exchangers, which are a typical component of cold-climate structures. According to the study's results, adding nanofluids to heat exchangers may lower the mass and space needed for heat transfer, which would lower the total amount of power needed for pumping [81]. The need for smaller heating systems that can deliver the same thermal energy as bigger systems using base fluids but are less expensive lowers the initial equipment cost, excluding the cost of the nanofluid. They are also a more ecologically friendly choice because to their reduced electricity and trash generation [82].

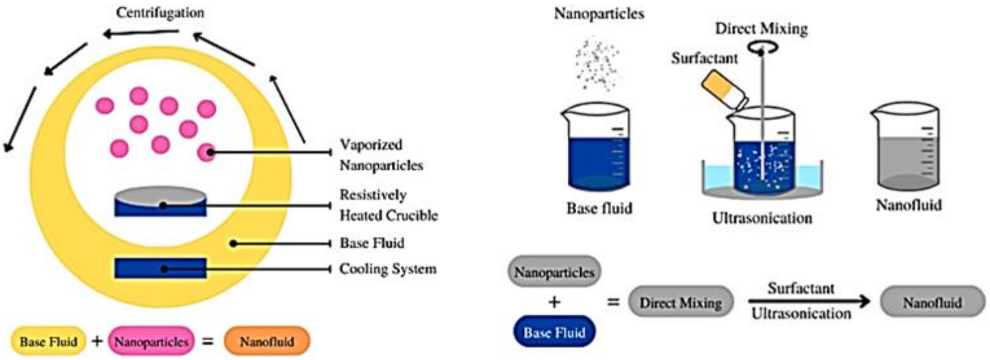
Additionally, there is evidence that nanofluids can improve nuclear reactor performance and safety [83]. In particular, the application of nanofluids in pressurized water reactors (PWRs) has been shown to increase critical heat flux (CHF) values by as much as 32%, which would allow for a 20% increase in the power output of current power plants [83]. Additionally, it has been shown that adding nanofluids to emergency cooling systems raises reactor safety limits, protecting the core's integrity in dangerous mishaps. Nanofluids, often known as smart fluids, provide novel approaches to energy management [84].

Another interesting area for nanofluids is their biomedical applications. In the biomedical field, the use of nanofluids is widespread in many applications, including antibacterial and drug delivery systems [85,86]. Various suspensions of biocompatible nanoparticles have recently become widely used in clinical trials and biological research under certain conditions. It has been stated that these useful suspensions are generally defined as nanofluids. They provide the dispersion and behaviour of nanoparticles in a uniform and stable environment. The benefits of nanofluids in biological techniques in various disciplines have been introduced in several publications. The main biological uses of nanofluids in imaging, drug delivery systems, and antibacterial properties are increasing. For example, the use of magnetic nanofluid systems is an important method for differential diagnosis, hyperthermia, and targeted drug delivery. In order to fight antibiotic resistance, nanofluids may potentially be employed as an antibacterial agent [85–88]. In particular, targeted medication delivery and controlled drug release are possible with nanofluids made of gold and silver nanoparticles [89,90]. Recently, nanofluids derived from carbon nanotubes (CNTs) have been reported to offer a new solution for drug delivery systems thanks to their inherent antibacterial properties [91–93]. The wide range of potential applications of nanofluids, together with their significant advantages in areas such as industry, energy, electronics, and biomedicine, is proof of their effectiveness. However, further research is needed to overcome challenges such as long-term stability and high production. However, the improved heat transfer properties of nanofluids can potentially minimize energy use, leading to cost savings and a more environmentally friendly profile. However, the relatively high production costs of nanofluids are a significant obstacle to the wider adoption of this technology. However, future cost reductions are expected to facilitate the integration of nanofluids into a wider range of applications.

2.1. Production methods of nanofluids

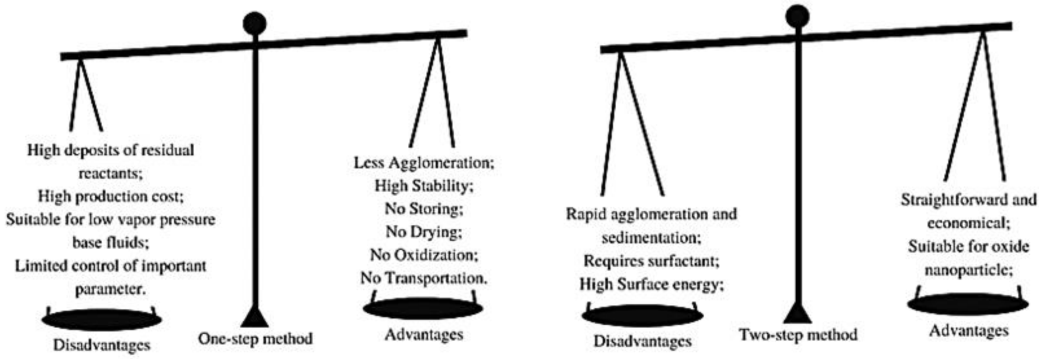
Stable colloidal suspensions of nanoparticles in solvents have long been called “nanofluids.” Several controversial discoveries in the literature have focused on unexpected improvements in the thermophysical properties (e.g. thermal conductivity) of nanofluids. This has attracted considerable attention from many research groups over the last three decades and has led to hundreds of papers on a variety of nanofluid-related topics, from basic studies to a wide range of applications in biological sciences and engineering. A wide variety of methods can be used to disperse selected nanoparticles in liquid solvents to adjust the size, shape, morphology (surface functionalization), material composition, structure, and mass concentration of the nanofluid [94,95].

In the context of experimental research involving nanofluids, a fundamental first step is the preparation phase. The process of dispersing solid particles in liquids is only one of the steps required to create nanofluids; additional criteria include ensuring a stable and uniform suspension, preventing particle aggregation, and durability, and preserving the chemical structure of the particles and the base liquid [96]. Typically, base liquids such as water, ethylene glycol, and oil are used in admixture with nanoscale solid particles to obtain nanofluids. However, aggregation or sedimentation of particles represents a significant challenge in this process [54]. Two basic approaches are generally used for the production of nanofluids: one-step and two-step methods [97]. In the one-step approach, the formation of nanoparticles and their dispersion into the base liquid occur simultaneously [98]. In early research, oxide particles such as Aluminium oxide (AlO_3) and copper oxide (CuO) were typically used due to their ease of production and chemical stability. However, the tendency of the particles to aggregate and their inability to produce pure metallic nanoparticles are significant disadvantages of this method [99]. In the two-step procedure, powdered nanoparticles are used, which are commercially available or can be manufactured. This process involves initially producing or purchasing nanoparticles that are then released into the base fluid. Ultrasonic instruments are often used in this step to reduce particle aggregation and ensure uniform dispersion. Additionally, techniques such as adding surfactants or controlling pH are used to improve the stability of the suspensions. While this technique has limitations when it comes to metallic nanoparticles, it works very well for preparing oxide nanoparticles. Surfactant stabilization changes the properties of the particle surface and reduces the tendency to aggregation; however, it should be noted that surfactants have the potential to impair heat transfer efficiency, especially at high temperatures. Both techniques for creating nanofluids have advantages and disadvantages. While the one-step method has limited fluid compatibility, it is useful in reducing aggregation and combining processes. Conversely, the two-step method offers improved flexibility and cost-effectiveness; however, achieving stability may require additional processing. The choice of method depends on the type of nanoparticles, the base fluid, and the intended application of the nanofluid.



(a) One-step method

(c) Two-step method



(b) Advantages and disadvantages of one-step method

(d) Advantages and disadvantages of two-step method

Fig. 1. (a) One-step technique, (b) One-step method benefits and drawbacks, (c) Two-step technique, and (d) Two-step method benefits and drawbacks. *("Reprinted (adapted) with permission from* [96]. *Copyright 2024 Elsevier.")*

Nanoparticles must be evenly distributed throughout the carrier fluid in order to create a stable nanofluid [100]. The effective creation of a stable nanofluid depends critically on the uniform dispersion of nanoparticles in the carrier fluid. In order to improve the dispersion process and raise the stability of the nanofluid, surfactants are frequently added to the carrier fluid [101]. Metal oxides, carbon-based nanoparticles, metallic nanoparticles, or hybrid nanofluids—a mix of the aforementioned—can all be used to create nanofluids. For example, Cu, Zn, and Al nanofluids are formed from metallic nanofluids. Metal oxide nanofluids, which include ZnO, CuO, aluminum oxide (Al_2O_3), and titanium oxide (TiO_2) nanoparticles with increased thermal conductivity, are another classification for nanofluids [102]. Metal oxides have been the subject of research. The performance of single basin, single slope solar stills with and without water nanofluids was investigated in one such research. The thermal and physical characteristics of water nanofluids, including those of Al_2O_3, ZnO, iron oxide (Fe_2O_3), and tin oxide (SnO_2), have been described. Two experimental stills of the same catchment area were established and tested simultaneously with water and various nanofluids to demonstrate the selection of suitable nanofluids for performance testing in solar stills. According to the report, the production of the still using ZnO and SnO_2 nanofluids was 12.67% and 18.63% higher than the still using water, respectively, while the production of the still using Al_2O_3 nanofluid was reported to be 29.95% higher [103].

According to a different study, it was reported that the bent tape inserts with different cutting radii in Hairpin heat exchanger were analyzed experimentally. It was reported that the friction factor of the whole pipe increased by 1.21 times for 0.03% nanofluid concentration with r=6 section radius compared to bent tape insert with H/D=3 water. According to the findings of the study, it was emphasized that when the volume concentration of nanofluid increases, the performance parameter of the heat exchanger, i.e. the heat transfer coefficient, also increases the friction factor [104]. In a separate study, an experimental investigation was conducted to examine the impact of incorporating nanoparticles into paraffin wax. It was reported that the addition of Al_2O_3 to paraffin wax led to a reduction in charging time by 2.1%, 5%, and 6.4%, respectively, when nanoparticles were introduced at concentrations of 0.1%, 0.2%, and 0.3%. Furthermore, it was reported that adding CuO to paraffin wax could reduce the charging time by 2.7%, 6.25%, and 8.8% after adding Nanoparticles at 0.1%, 0.2%, and 0.3% weight concentration, respectively. It was emphasized that paraffin wax showed good thermal conductivity response [105]. Images of studies using nanofluids of different sizes and shapes are shown in Figure 2.

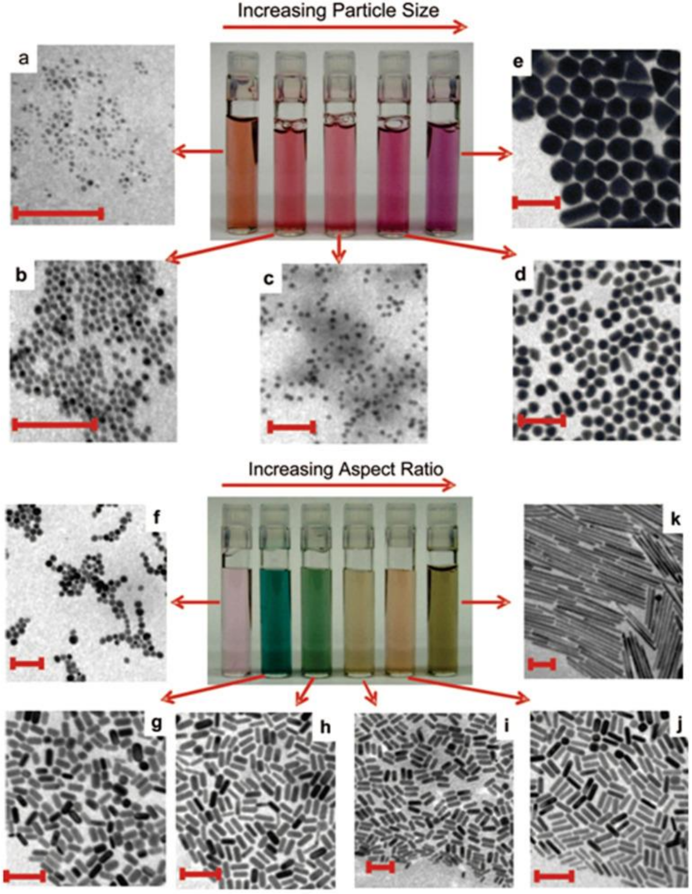


Fig. 2. Images of gold nanospheres (top panels) and gold nanorods (bottom panels) in aqueous solutions as a function of increasing size. For rods, the color difference between the particle solutions is more pronounced than for spheres. This is because the plasmon bands - two for rods and one for spheres - are more sensitive to size in rods than in spheres. Aspect ratios for rods range from 1.3 to 5 for short rods (TEMs f-j) to 20 (TEM k) for long rods, whereas spheres range in size from 4 to 40 nm (TEMs a-e). *"Reprinted (adapted) with permission from* [106]. *Copyright 2024. American Chemical Society."*

As previously mentioned, carbon-based nanoparticles such as single walled carbon nanotube (SWCNT), multiwalled carbon nanotube (MWCNT), and graphene, among others, have excellent thermal conductivity and increase the viscosity of the fluid. Hybrid nanofluids represent a combination of different nanoparticles, for example, Al_2O_3 + MWCNT, Fe_3O_4 + SWCNT, etc. [107]. In existing literature, a significant amount of research has been devoted to the study of hybrid nanofluids. In this work, a unique chemical reduction procedure followed by low-temperature calcination was used to create copper oxide decorated graphene (CuO/HEG). The thermal transport characteristics of these nanofluids were examined when CuO/HEG was dispersed in ethylene glycol and deionized water without the use of a surfactant. According to the study, with a volume percentage of 0.05%, the thermal conductivity of CuO/HEG dispersed in a DI water-based nanofluid rose by around 28% at 25 °C [108]. In a similar hybrid nanofluid application, a hybrid water-based suspension of Al_2O_3 nanoparticles and microencapsulated phase change material (n-eicosane) particles (MEPCM) was produced. According to research, the intrinsically poor thermal conductivity of pure PCM suspensions can be effectively improved by dispersing a larger proportion of Al_2O_3 nanoparticles, which can lead to a much higher thermal conductivity compared to purified water [109]. In another study, a new synthesis process for silver-functionalized hydrogen derivative exfoliated graphene (Ag/HEG) was also described. Due to their excellent thermal conductivity, graphene and silver nanoparticles are used to form Ag/HEG nanofluids. Ag/HEG nanofluids were prepared by dispersing the material in ethylene glycol and deionized water using ultrasonic agitation, which produced a uniform dispersion without the need for a surfactant. According to the study, the thermal conductivity and heat transfer properties of Ag/HEG dispersed nanofluids were better than those of the base fluid. It was emphasized that the synthesized nanofluid showed stability for more than three months and the Ag/HEG dispersed deionized water-based nanofluid increased by approximately 25% for a 0.05% volume fraction at 25 °C [110].

2.2. Nanofluids & Solar Cells Applications

Solar energy is defined as an energy source that is obtained by converting electromagnetic radiation reaching the Earth's surface from the sun into electrical or thermal energy [111]. This energy source is considered to be one of the most critical components of sustainable energy strategies due to its renewable, unlimited, and clean nature [112]. Solar energy stands out with its environmental advantages, such as reducing carbon emissions and reducing dependence on fossil fuels. It also has the potential to reduce economic costs and increase energy independence [113].

There are different systems among solar energy technologies. Photovoltaic systems are based on semiconductor materials that directly produce electrical energy, whereas concentrated solar power (CSP) systems produce thermal energy by concentrating the sun's rays to a focal point with the help of mirrors or lenses. CSP systems generally convert the heat obtained into electrical energy through steam turbines [114]. Solar thermal systems, on the other hand, use concentrated heat in areas such as water heating, industrial processes, or space heating. Dual-use hybrid systems are designed to be used in both electrical and thermal energy production. In solar energy systems, cooling techniques are vital components [115]. The use of an efficient cooling system is essential to preserving energy efficiency and prolonging system life, whether in photovoltaic panels or concentrated solar energy facilities [116]. As the electrical efficiency of solar panels declines with increasing working temperatures, either active cooling systems (supported by a pump or fan) or passive cooling methods (based on air or liquid) are employed [117]. In CSP systems, the transfer of concentrated heat and the protection of steam systems from overheating can be achieved by water-based or nanotechnology-supported cooling techniques [118]. These cooling techniques ensure energy efficiency while preventing mechanical components from being damaged by high temperatures. The use of innovative nanofluid technologies is increasing in CSP systems to enhance cooling capacity and prolong system life [119]. These technologies significantly increase the heat transfer coefficient, thereby maximizing system performance. These technologies, supported by advanced modelling and analysis, ensure a future where solar energy systems will be more extensively and efficiently utilized [120]. The representation of Linear and CSB Solar Panels is given in Figure 3. The need for certain cooling units in both structures has been particularly emphasized in the literature and industrial applications.

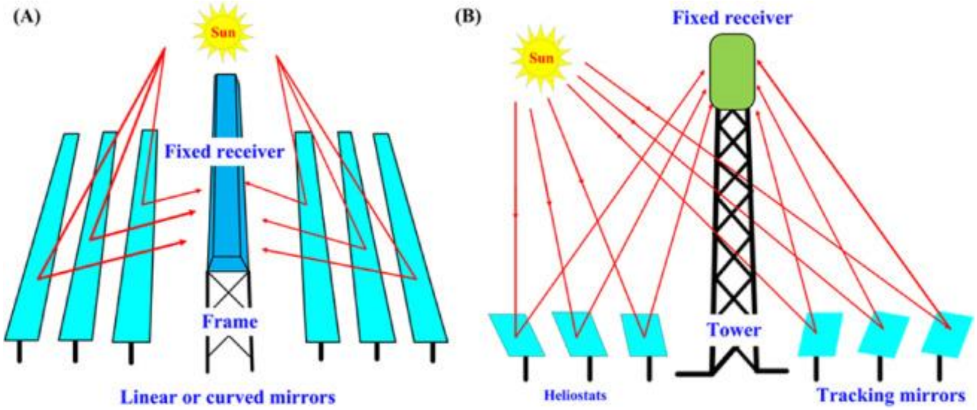


Fig. 3. A) Linear fresnel reflectors and B) Solar towers are used in the CSP's schematic structure *("Reprinted (adapted) with permission from* [118]. *Copyright 2024 Elsevier.")*

Thermal devices known as solar collectors absorb sunlight and convert it into thermal energy. The working fluid is the most important component of solar collectors as it absorbs sunlight as it passes through the collector tubes in these systems. Water and other liquids are often used for this function, but they suffer from low efficiency [121]. The use of nanofluids to increase collector efficiency has been the subject of several investigations. When used instead of water, nanofluids are a unique substitute that significantly improves thermal performance [122].

The useful heat gain of the working fluid of a solar collector is expressed by the following equation (Eq.1) [123,124]:

$$Q_u=\dot{m}\,Cp(T_{out}-T_{in})\ (\mathrm{kW}) \tag{1}$$

Here Q_u represents the useful heat gain (kJ), $\dot{m}$ represents the mass flow rate of the liquid (kg/s), Cp represents the heat capacity of the liquid at constant pressure (kJ/kg.K), and Tout and Tin represent the outlet and inlet temperatures (K), respectively. The thermal efficiency of the solar collector is defined as follows(Eq. 2) [125]:

$$\eta=Q_u/I_TAC\ (\%) \tag{2}$$

Here I_T is the incident solar radiation (W/m^2) and AC is the collector area (m^2). The specific heat of the nanofluid used as a working fluid is calculated as follows (Eq. 3) [126]:

$$C_{p,nf}=(1-\phi)\rho_{bf}C_{p,bf}+\phi\rho_{np}C_{p,np}/\rho_{nf} \tag{3}$$

Here, $C_{p,nf}$ represents the specific heat of the nanofluid, Cp,bf and Cp,np represent the specific heat of the base fluid and nanoparticles (kJ/kg.K), ϕ represents the volume fraction of nanoparticles in the nanofluid, ρnf, ρbf, and ρnp represent the density of the nanofluid, base fluid and nanoparticles (kg/m^3), respectively. The density of the nanofluid is calculated as follows (Eq.4) [127]:

$$\rho_{nf}=(1-\phi)\rho_{bf}+\phi\rho_{np} \tag{4}$$

According to these equations, to maximize the collector efficiency, it is necessary to increase the useful heat gain. This can be achieved by increasing the mass flow rate ($\dot{m}$) of the working fluid for a fixed incident solar radiation and collector area, improving its specific heat (C_p), or increasing the difference between the inlet and outlet temperatures.

These equations show that increasing the usable heat gain is necessary to maximize collector efficiency. This can be accomplished by raising the working fluid's specific heat, the temperature differential between the inlet and exit, or the fluid's mass flow rate for a certain incoming solar energy and collecting area [128]. Nanofluids can directly affect these parameters through the physical characteristics of the nanoparticles that are introduced to the base fluid. Nanoparticles' low specific heat allows them to absorb heat more quickly, while their enormous surface area and superior thermal conductivity allow heat to be transmitted to the base fluid more fast [63]. Through the enhancement of the physical characteristics of the nanoparticles introduced to the base fluid, nanofluids could directly influence these parameters. Because of the nanoparticles' low specific heat, heat is absorbed more quickly, and because of their huge surface area and strong thermal conductivity, this heat is transmitted to the base fluid more quickly. This procedure raises the collector's overall efficiency by raising the output temperature [129].

Studies have shown that the use of nanofluids as working fluids can increase the efficiency of solar collectors by up to 5% [130]. In contrast to surface-based absorption, the use of nanofluids as volumetric absorption media offers better absorptivity and reduced reflectance [131]. According to the studies in the literature, it has been stated that the contrast spectra generated from the reflected light of a white light source can be used to distinguish between single, double and multilayer (less than ten layers) graphene on a Si substrate with a 285 nm SiO_2 coating. It has been shown that the calculations based on Fresnel's law and experimental results are in good agreement (within 2%). Based on the contrast spectra, it has been stated that there are two simple technical methods to calculate the number of graphene layers [132]. Another research investigated the applications of nanofluids in direct absorption of solar radiation in volumetric solar collectors. It was reported that the mass, momentum and energy equations were solved together with the radiation transport equations to simulate the operating characteristics of the direct absorption solar collector. Different diameters and volume fractions of graphite nanoparticles were investigated and for each case the efficiency of solar collectors in absorbing solar energy, the effects on the harvested solar energy, the irradiance spectrum distribution and the irradiance energy level with respect to the flow depth were studied. The data obtained showed that by using graphite nanofluids with a volume fraction of about 0.000025%, it would be possible to absorb more than 50% of the incident solar energy with an increase of only about 0.0045 $/L, while pure water solar collectors could only absorb about 27% of the incident solar energy [133]. The feasibility of using a non-concentrating direct absorption collector (DAC) was investigated theoretically in another study comparing its performance with that of a standard flat plate collector. The absorbing medium used was a nanofluid, a combination of water and aluminum nanoparticles. The results indicated that a DAC using a nanofluid as the working fluid achieved up to 10% higher efficiency (in absolute terms) than a flat plate collector under comparable operating conditions. It was emphasized that a DAC using a nanofluid as the working fluid generally outperformed a flat plate collector [134]. In a related paper, carbon black nanoparticles were used in water at concentrations ranging from 0.005 to 0.020 weight percent to create a nanofluid. Compared to the base fluid, a 102% thermal improvement was found at the ideal nanofluid concentration of 0.010 weight percent [135]. As can be seen from these studies, it can be said that nanofluids have been used extensively in solar cells for many years.

2.3. Nanofluids and nuclear reactor applications

Nuclear energy represents a very powerful form of energy produced by the splitting or merging of atomic nuclei through fission or, less commonly, fusion [136]. The basis for choosing nuclear energy is its significant contribution to combating climate change due to its incredibly low carbon emissions, and its high energy density, which can reduce dependence on traditional fossil fuels [137]. However, there are other problems to be solved, such as the high upfront costs of using nuclear energy, waste management problems, and security threats [138]. To be used in industrial processes such as electricity generation, this energy must undergo a series of changes. During the fission process, free neutrons attack isotopes such as uranium-235 and plutonium-239, producing significant amounts of energy. The steam systems used for electricity generation receive this energy from fuel rods located inside the reactor bellows [137,139–144]. Fission reactors are currently the dominant nuclear energy technology; however, additional reactors based on fusion processes are theoretically under construction. The fusion process combines lighter atomic nuclei (hydrogen isotopes such as deuterium and tritium) to produce a heavier nucleus with a significantly higher energy content. The Sun and other stars are known to produce energy by fusion, which theoretically provides a clean and unlimited source of energy. Fusion energy has attracted significant attention because of its extensive fuel supply, high safety, and minimal radioactive waste. However, the stability of the plasma and the regulation of extremely high temperatures pose significant challenges to the development of this technology [145]. Nuclear power plants generally consist of reactor blowers, turbines, cooling units, and control centers [146]. Mini nuclear reactors can vary in structure [147]. The primary area where the nuclear process takes place is the reactor pits, along with the control rods. Fuel rods, usually made of enriched uranium, regulate the reactor's energy efficiency and work with control rods, usually made of neutron-absorbing materials such as boron or cadmium, to sustain the nuclear reaction [148]. The primary cooling circuit carries the heat released by the reactor to the steam generators. The turbine system is driven by the steam produced in the steam generator, thus converting mechanical energy into electrical energy [149–152]. The working scheme of a nuclear power plant with PWR is shown in Figure 4.

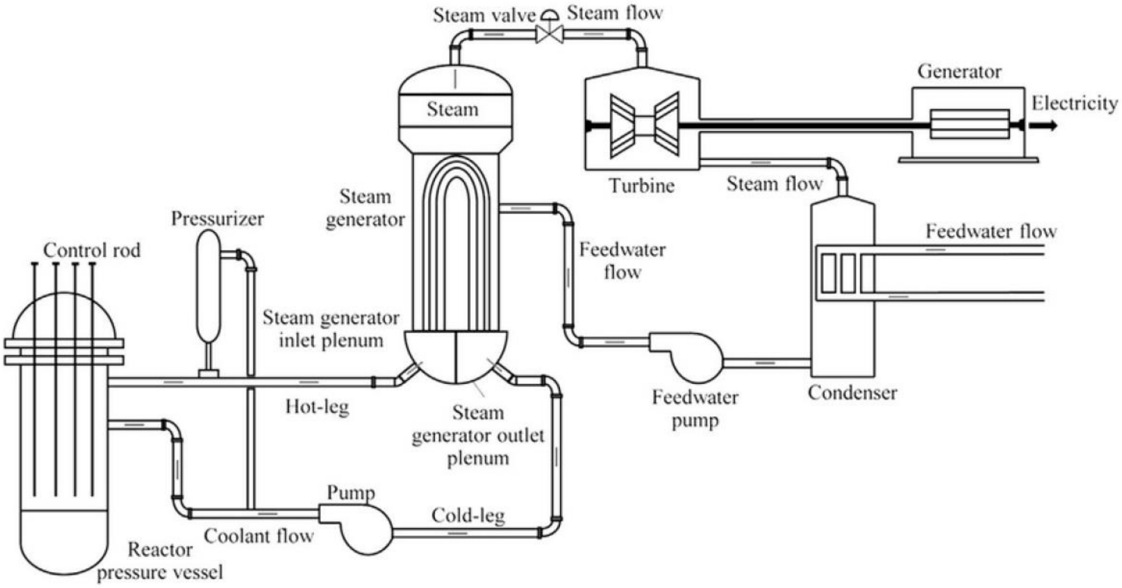


Fig. 4. Operating equipment of a nuclear power plant with a PWR. *(Reprinted (adapted) with permission from* [153]. *Copyright 2025 MDPI.)*

The first important step of the cooling system in nuclear power plants begins here. This technology uses a water-based cooling medium designed to regulate the excess heat produced in the reactor and to transmit this energy to the grid. Apart from these, gases such as carbon dioxide and helium can be used as coolants [154]. Adding chemicals to water cooling systems is an effective measure to increase system performance and reduce the effects of corrosion. Chemical balances are to maintain the pH balance of the water. The second cycle involves the use of cooling towers, which help maintain the balance by releasing heat into the atmosphere as steam [155].

The safety and continued operation of nuclear power plants depend on the efficient operation of cooling systems. While reactor heat conversion is optimized through the use of materials with excellent thermal conductivity and creative designs, systems with desired nanostructures are reported to be becoming more common as one of these material classes [156]. It is known that the increased thermal conductivity of nanofluids greatly exceeds the heat transfer capacity in nuclear reactors and the capacities of traditional fluids such as water, and therefore they are especially preferred in cooling units. This increase in efficiency has led to a decrease in thermal-hydraulic problems and paved the way for advanced energy optimization. The heat transfer of nanofluid can be attributed to various factors such as volume concentration, physical properties, and the size of nanoparticles [157]. There are many studies on nuclear reactors in the literature. One study numerically investigated the performance of aluminum-based nanofluids for potential use in pressurized water reactors. At the highest speeds (Re = 80,000) and maximum volume concentrations ($\phi = 4\%$), the maximum heat transfer coefficient of the nanofluid was calculated. It was reported that the heat transfer with 4% Al_2O_3 was 1.09 times higher than that of the base fluid [157]. As emphasized in the literature, it can be said that nanofluids will be a very good material in cooling systems. Due to the high thermal conductivity of nanofluid, the heat transfer capacity in nuclear reactors can be thousands of times higher than that of traditional fluids such as water. In the study, the properties of SiO_2-water-based nanofluids were used in numerical research to improve heat transfer in light water reactors. In the study, the functions of nanofluid such as heat transfer, volume concentration, physical properties and nanoparticle size etc. were investigated. It was emphasized that nanofluid plays a very important role in improving heat transfer in nuclear power plants. In the study, the importance of nanofluid in carrying heat in the reaction chamber was emphasized [158]. The benefits of nanofluids in cooling units in nuclear reactors are frequently mentioned in many institutions and organizations.

2.4. Nanofluids and biomedical applications

Nanofluids offer a wide range of uses, naturally including applications in the medical field, where their unique properties are particularly advantageous. Their use in a variety of biological applications is steadily increasing, driven by their unique properties. The development of medical technologies and their potential to enhance human health is significantly influenced by the biomedical use of nanofluids [159]. A prominent application of nanofluids in the biomedical industry is cancer treatment [19]. They utilize magnetic fields to facilitate controlled movement, thereby enhancing the efficiency of drug loading and targeting systems. This approach ensures the safety of healthy tissues while enhancing the efficacy of chemotherapy drugs [160]. Another significant biological application of nanofluids is hyperthermia therapy, a therapeutic technique that utilizes heat to target and destroy malignant cells [161]. The effectiveness of this therapy is enhanced by the delivery and controlled heating of magnetic nanoparticles using nanofluids, which can effectively target and kill malignant tissues due to their ability to be heated by a magnetic field [162]. Additionally, nanofluids are employed in medical imaging methods [86]. Nanofluids function as contrast agents, thereby enhancing the quality of imaging in a range of medical technologies, including computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound. This enhancement enables more precise and clearer visualization of target tissues [163]. Notably, magnetic nanofluids have garnered popularity in the field of MRI contrast agents. A literature review of this field of application compared the efficiency and energy savings of a thermosyphon heat exchanger filled with methanol-silver nanofluid and pure methanol. The data obtained shows that the use of methanol-silver nanofluid resulted in energy savings of approximately 8.8-31.5% for cooling and 18-100% for warming the supply air flow in an air conditioning system[164]. Thanks to the physicochemical properties of nanomaterials, such as self-organization and surface modifiability, these specific nano contrast agents can greatly improve the targeting of lesions by various preparation methods and highlight the distinction between lesions and normal tissues in both CT and MRI. As a result, they have the potential to be used in the early stages of disease to improve the diagnostic abilities and level of medical imaging [163]. In addition, medical imaging methods make use of nanofluids. These serve as contrast agents that enhance picture quality in technologies including computed tomography (CT), magnetic resonance imaging (MRI), The use of specially designed nanoscale particles enables the visualization of target tissues with enhanced clarity and precision. Of note are magnetic nanofluids, which are extensively utilized as MRI contrast agents. A further pioneering application of nanofluids lies in biosensors, where their optical and electrical properties contribute to enhanced interactions with biomolecules, thereby augmenting biosensor sensitivity. These technologies are indispensable for the monitoring of biomolecules and the early detection of diseases [165] .

Another notable application of nanofluids lies in biosensors. Biosensors are used in a variety of fields, including biochemistry, electrochemistry, agriculture, and the biomedical industry. Food, healthcare, environmental monitoring, water quality, forensics, drug development, and biological sciences are just a few examples of point-of-care applications that they can include [166]. Miniature biosensors have been developed and manufactured using a variety of techniques, including design, optimization, characterization, and testing [167]. Due to their high-affinity interactions with biomolecules, they are used for the sensitive detection of analytes even in small sample volumes. Microfluidics, which uses fluid mechanics to control small biosensors, is one of the few development methods that is gaining the most interest [168]. Existing conventional devices are difficult to automate, integrate, and miniaturize for a variety of applications because they are large, costly, slow-acting, and require human interaction. Microfluidic biosensors, which have a small reaction volume for sensing, offer the advantages of mobility, operational transparency, controllability, and stability. The design, categorization, developments, and challenges of microfluidic-based biosensors are discussed in this review of biosensor technology [169]. The value chain (including manufacturing and other associated protocols) for the development of miniature microfluidic-based biosensor devices for use in various point-of-care diagnostic applications is meticulously examined. The optical and electrical characteristics of nanofluids enhance their interactions with biomolecules, thereby boosting biosensor sensitivity. These technologies are essential for tracking biomolecules and for early illness detection. The heating of these nanoparticles by a magnetic field results in their effective destruction of malignant tissues [170].

3.Future Perspective of Nanofluidic in Mechanical Engineering

Nanofluids, which possess enhanced thermal conductivity and the capacity to enhance heat transfer efficiency, hold considerable promise for utilization in mechanical engineering applications, including heat exchangers, cooling systems, and thermal management. Nevertheless, their effective implementation in commercial systems is contingent upon the resolution of numerous significant obstacles, the most salient of which pertains to the stability of the nanofluid [110]. In mechanical engineering, the stability of the nanofluid can have a considerable influence on the performance of systems such as industrial cooling units, engine cooling systems, and refrigeration technologies, especially in long-term operations [171]. Instability, which is commonly exhibited as nanoparticle aggregation or settling, results in lower performance and may cause blockages or inefficiencies in heat transfer operations. Therefore, addressing nanofluid stability is critical to ensure their effectiveness in mechanical systems. Following established engineering principles, it is imperative to formulate nanofluids that exhibit consistent dispersion over time [172]. The utilization of appropriate surfactants during the synthesis process plays a pivotal role in stabilizing nanofluids by preventing nanoparticle clustering. This consideration assumes particular significance in applications necessitating a uniform distribution of nanoparticles within the base fluid, such as cooling systems and heat exchangers, where thermal conductivity must remain constant throughout operation [173]. A significant engineering method involves the functionalization of nanoparticles with specific chemical groups that facilitate robust connections, such as hydrogen bonds, between the particles and the base fluid. This enhances the nanofluid's stability and leads to increased thermal conductivity, as demonstrated by Christensen et al. in their grease formulation study [174]. Mechanical engineers must exploit these interactions to enhance the performance of lubricants, cooling fluids, and other heat transfer media utilized in machinery, engines, and turbines [175]. Furthermore, environmental elements such as temperature, pH, and pressure, which are pivotal parameters in thermodynamics and fluid mechanics, exert an influence on nanofluid stability in mechanical systems. An increase in temperature can generate more particle motion, thereby reducing inter-particle forces; however, it can also enhance the fluid's convective heat transfer characteristics [176–178]. Mechanical engineers must evaluate the impact of elevated temperatures on the dynamics of nanofluids, particularly in systems where thermal stability is paramount, such as in automobile engines or aircraft cooling systems [179]. It has been demonstrated that reducing the pH below the nanoparticles' isoelectric point (IEP) increases electrostatic repulsion, decreases agglomeration, and improves fluid flow characteristics. According to the principles of fluid dynamics, this method maintains laminar flow and minimizes viscosity in order to effectively transmit heat [179]. One effective way to break up nanoparticle agglomerates and achieve a more uniform particle size distribution throughout the production process is to use high-shear and high-pressure homogenizers. This approach is consistent with engineering concepts that regulate particle size and distribution to achieve optimal heat transfer and flow outcomes.

Future studies should focus on developing improved production processes and exploring novel surfactant types that are specifically tailored to the chemistry of the nanomaterial and the base fluids. [180,181], [182]. Engineers will be able to create better fluid formulations for certain applications, such Heating, Ventilating and Air Conditioning (HVAC) systems, microprocessor cooling, and industrial equipment cooling, with a better knowledge of these chemical interaction [164]. Determining the best nanofluid compositions for a range of industrial applications requires a thorough examination of the attributes of mass and heat transport as specified by engineering principles. New nanomaterials with the potential to increase the thermal conductivity of nanofluids include MXene, 3D graphene, and metal oxide nanocrystals [183–185]. As mentioned, nanofluids have been reported to increase heat transfer rates. The addition of copper nanoparticles prepared with ethyl glycol increased heat transfer by a factor of 2.5. This property is highly advantageous in heat exchangers, radiators and other cooling systems [186]. In mechanical engineering, nanofluids are also used in thermosyphons and significant reductions in thermal flow resistance have been reported. At the same time, it has been reported that significant advantages are gained by improving efficiency in cooling. However, the integration of nanofluids into the existing system is an important concern due to compatibility and cost [187]. These innovative materials have the potential to enhance the performance of mechanical systems that require effective heat dissipation, including power plants, refrigeration units, and automobile cooling systems [185]. From a materials engineering standpoint, the usage of these new nanomaterials may result in the production of next-generation nanofluids with improved thermal and mechanical characteristics [75]. Finally, further research is needed on nanofluid performance under various operating conditions, including severe temperatures, high and low pressures, and magnetic field exposure [188]. In particular, valuable insulation materials need to be developed to overcome significant shortcomings and problems in thermal applications [189]. Research is still needed to overcome the identified thermal and insulation shortcomings. Additionally, the extreme circumstances that mechanical systems—like those utilized in aviation engineering—are often subjected to potentially affect their thermal efficiency and fluid stability [190]. To increase their usage in high-performance applications like nuclear reactors and spacecraft cooling systems, a precise knowledge of how nanofluids behave under these diverse circumstances is crucial. Resolving issues with stability, material selection, and nanoparticle distribution is necessary to achieve broad commercial applicability [191]. Therefore, future research should concentrate on utilizing basic mechanical engineering principles like fluid dynamics, thermodynamics, and materials science to maximize the utilization of nanofluids for complicated applications, such as industrial cooling and high-performance energy systems [1].

4. Conclusion

In mechanical engineering, nanofluids are a novel class of materials that have the potential to increase the effectiveness of cooling and heat transfer systems. Particle size, nanoparticle alignment (e.g., carbon nanotubes (CNTs), graphene, metal, and metal oxide nanoparticles), liquid pH, base liquid type, and temperature all have an impact on these materials' thermophysical characteristics. Understanding the behavior of these materials is made extremely difficult by the intricate interactions between these characteristics, which together influence the thermal conductivity of nanofluids. The existing literature presents several inconsistent findings, especially regarding the effect of temperature, and no clear consensus has emerged regarding the effect of these factors on thermal conductivity. It is imperative to acknowledge that the factors affecting the thermal conductivity of nanofluids are not limited to direct effects only but also include indirect effects such as viscosity and stability, which play an important role in determining the overall performance of these materials. These factors determine the overall performance and effectiveness of nanofluids in practical applications. Furthermore, to maximize the stability of nanofluids, mechanical, magnetic stirring, ultrasonic, and chemical stabilizer-assisted dispersion techniques are commonly employed. While high-frequency vibrations from the ultrasonic approach offer homogenous dispersion, low-viscosity liquids can be stirred mechanically or magnetically, albeit these methods may lose their efficiency with time. Chemical stabilizers alter surface charges to stop sedimentation. One of the best techniques is ultrasonic dispersion, and stabilizers are known to improve stability over the long run. However, the stability of nanofluids and the long suspension times of nanoparticles in liquids may create obstacles for commercial applications. There is an increasing focus on nanofluids in mechanical engineering applications, and significant advances are being observed in areas such as heat transfer, cooling systems, microprocessor cooling, industrial cooling, solar energy systems, and nuclear reactors. Because of their excellent heat conductivity, low viscosity, and energy efficiency, nanofluids are used in these systems. The development of cooling systems for engines and microprocessors is a noteworthy example of this, as nanofluids can enhance overall performance by enabling more effective heat transmission. Nonetheless, studies on the potential of nanofluid compositions with different nanoparticle sizes and kinds indicate that these materials may find usage in a greater variety of commercial applications. From medicine delivery applications to lubrication systems, such novel nanofluid formulations may provide creative answers in a variety of fields. To fully maximize these materials' potential, additional research and development is necessary. In this regard, future mechanical engineering applications will benefit greatly from nanofluid formulations comprising nanoparticles of various sizes as well as nanotechnological developments.

Author Contribution

Hasan D. Yildizay; draft creation, writing, figure permissions, editing. Muhammed Bekmezci; draft creation, writing, figure permissions, editing. Fatih Sen; draft creation, writing, figure permissions, editing, supervisor.

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