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Review

Recent Developments on the Thermal Properties, Stability and Applications of Nanofluids in Machining, Solar Energy and Biomedicine

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Abstract: In this review work, the recent progress made in the use of nanofluids (NFs) applied in three specific areas will be presented: machining, solar energy, and biomedical engineering. Within this context, the discussions will be guided by emphasizing the thermal and stability properties of these fluids. In machining, NFs play a prominent role in the processes of turning, milling, drilling, and grinding, being responsible for their optimization as well as improving the useful life of the tools and reducing costs. In the solar energy field, NFs have been used in the thermal management of the panels, controlling and homogenizing the operating temperature of these systems. In the biomedical area, the advantages of using NFs come from the treatment of cancer cells, the development of vaccines before the improvement of diagnostic imaging, and many others. In all lines of research mentioned in this study, the main parameters that have limited or encouraged the use of these fluids are also identified and debated. Finally, the discussions presented in this review will inspire and guide researchers in developing new techniques to improve the applications of NFs in several fields.

Keywords: nanofluids; heat transfer; nanoparticles; thermal conductivity

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1. Introduction

Nanofluids (NFs) are a colloidal mixture of nanoparticles (NP) (1–100 nm) suspended in a fluid base [1,2]. NPs can be metals, oxides, carbon-based nanomaterials, carbides, or polymers, while the most common base fluids are water, oil, and ethylene glycol [3,4]. The main application of NFs is in heat transfer. The idea of using small solid particles in a liquid to improve thermal efficiency has been known since the beginning of the 20th century [5], but the first to consider using nanoscale particles for this purpose was Choi [1,6] in a theoretical study. One of the first experiments dates back to 1997 when Eastman et al. [7] significantly increased the thermal conduction of water and oil. Currently, nanofluids have been increasingly investigated [5], and it is believed that the most promising studies will be those involving multidisciplinary contributions [3].

The improvement of thermal properties by adding NPs to the base fluid is due to a large specific surface area that allows a large heat exchange, Brownian movement, and the possibility of varying the properties by raw material, in addition to permitting a more efficient use of pumps requiring smaller cooling systems [2]. To obtain the NPs, two techniques are used, the one-step and two-step methods [1,5,8]. The one-step method combines NPs preparation and fluid synthesis, which tends to improve stability. The NPs are prepared by physical vapor deposition (carbon nanotubes) or by the chemical liquid method (Copper nanofluid) [8–10]. In the two-step method, NPs are first produced in processes such as dry powder by inert gas condensation (aluminum, copper, molybdenum, platinum, titanium, and iron oxides Nps) [11], mechanical alloying (Ni_3S_2, Mg_2Ti_4, $CoFe_2O_4$) [12–14], chemical vapor deposition (Boron nitride nanotubes, Carbon nanotubes, Fe_3O_4) [15–17], or chemical deposition (PbS) [18], and, after the appropriate separation and drying processes, are dispersed in the fluid [8,19]. As the tendency of agglomeration is greater in this step, methods such as ultrasonic agitation and the addition of surfactants are used to improve the dispersion and thermal properties [8]. There are applications of nanofluids in various heat exchange systems for engines, solar panels, nuclear, and space areas, as well as their use in biomedical, machining, and energy storage [2].The greatest interest to use is the potential improvement in the heat transfer properties of current fluids. Due to the small size of NPs, NFs are easily compatible with systems that use common fluids and, therefore, can be applied in conventional heat exchangers such as tube type, car radiators, refrigeration systems (as in Vapour Compression Refrigeration System) (VCRS) which allowed a significant increase in COP [20].

Antibacterial properties of NPs embedded in NFs may also contribute to slowing down their deterioration and improving their heat and mass transfer rates, such as silver nanoparticles in a modified solar desalination system [20,21].

NFs and NPs with thermoelectric effect allow the creation of electricity and thermal energy co-generators in solar light absorption systems. In this context, the optical properties of nanofluids can also open doors to the improvement of solar collectors [22].

NFs that use magnetic and dielectric NPs that are subject to electromagnetic waves allow changes in interfacial tension, changes in wettability and viscosity, and as a result makes this option a promising technology for crude oil extraction in porous media [23].

There are many areas of study in which nanofluids have been explored [24,25]. In the field of machining, this technology has been used for coolants and lubricants for turning, milling, drilling, and other operations [26]. Many works explore the improvement of the Minimum Quantity Lubrication (MQL) method and its influence on thermophysical, tribological, and wetting properties of NFs for this type of application [27]. In solar energy, the use of nanofluids has been widely studied as a form to improve heat exchangers in solar collectors, as presented in the review by Xiong et al. [28], focused on hybrid nanofluids. Adun et al. [29] used nanofluids as liquids for heat transfer in a parabolic collector achieving a significant increase in performance. Shoeibi et al. [30] and Abdelaziz et al. [31] achieved significant improvements in solar still. Hosseinzadeh et al. [32] increased the output power and energy efficiency of a solar cooker. Ibrahim and Saeed [33] increased not only the heat transfer but also the required pump power and the efficiency of a photovoltaic cell cooling system.

NFs can be useful in biomedicine/medicine in processes such as magnetic separation, bioassays, drug and therapeutic administration, cancer treatments, aid in diagnosis, and estimate mechanical and rheological properties of cells [34–36].

This work has as main objective to present a review of the main properties and applications of NFs in three main areas: machining, solar energy, and biomedical. A concise review of each topic is presented to demonstrate the limitations and possibilities of this type of technology.

2. Thermal Properties

Determining the properties of NFs is complex, and several groups have obtained different results due to the large number of variables involved in the process and difficulty in relating cause and effect in the variations of parameters [5,37]. Furthermore, the general thermal transfer properties of each system are determined by the characteristic of the solid-liquid interface [38]. The main thermal properties of NFs are presented below, together with the means by which they can be obtained.

Thermal conduction has its value affected by several parameters such as concentration, shape, size, temperature and thermal conductivity of NPs, type of base fluid, pH, sonication, and preparation technique [3,5]. Among recent techniques for measuring thermal conductivity, one can mention Xu et al. [39], who implemented and improved a Steady Flow Method (SFM) based on the theory of heat transfer in laminar flow under uniform heat flow. With this, the authors could reduce the influence of natural convection in the measurement process. Other techniques that can be mentioned are the transient hot-wire approach, which consists of a thin metallic wire that works as a thermometer and heat generator simultaneously. The wire is then immersed in the fluid and the rate of temperature change indicates the conductivity [40]. The parallel plate technique consists of placing small samples of NFs between two parallel copper plates (purity greater than 99%) connected to thermocouples. Thermal conduction is defined by the temperature variation of the plates when one of them is subjected to a heat source [41]. Amiri et al. [42] evaluated the impact of the Graphene Quantum Dot on the stability and thermal properties of a water-based solution. The results showed a significant increase in thermal conductivity when a very low concentration of NPs was placed.

Although it is of great importance, there is limited research concerning specific heat in articles concerning the physical properties of NFs [3]. The most common way to measure specific heat is through DSC (Differential Scanning Calorimetry). This test measures the difference in the amount of heat needed to increase the temperature of the analyzed material and is compared to reference material at the sequence [43]. There are derivations of this method that have brought some advances, such as the case of Temperature Modulated Differential Scanning Calorimetry (TMDSC) that varies the temperature with slight sinusoidal disturbances. Combined with a mathematical treatment, the method allows for greater sensitivity and the observation of other phenomena such as metastable melting [44] and Quasi-isothermal TMDSC varies the temperature at an insignificant rate [45]. Żyła et al. [43] used the Quasi-isothermal TMDSC method to determine the specific heat of Ethylene glycol-containing NPs from AlN, Si_3N_4, TiN. The author observed a large variation of the specific heat by increasing the concentration of particles without their size having a great influence.

Density influences Nusselt and Reynolds number, friction factor, and pressure loss [46]. As it is an easy parameter to obtain, it is measured by dividing the measured mass by a known volume or using a densimeter that works with these same principles. Mirsaeidi and Yousefi [47] determined the carbon density of quantum dots NFs using a densimeter.

Dynamic viscosity is the fluid's resistance to shear stress, being one of the most important properties of the fluid as it demonstrates its behavior close to the limits of a solid body. The viscosity directly affects the pumpability and pressure of the system [48]. One way to measure viscosity is through a capillary viscometer, where a tube with a short internal diameter (about 2.5 mm) comes vertically into contact with the NF, whose viscosity is determined by the variation in pressure and volumetric rate through Poieuille's law [49]. The cone and plate viscometer, on the other hand, consists of a static plate where the liquid is inserted, while above there is another conical plate that rotates. The distance between the two plates is very small to allow the fluid to contact the conical plate. As the top plate rotates, the drag force of the fluid is measured, and the viscosity can thus be determined [50]. A Couette concentric cylinder viscometer is a rotational viscometer. In this type of viscometer, two concentric cylinders have the space between them filled with fluid. The outer cylinder rotates, the inner one is stationary, and measurements of it are taken. Rajendiram et al. [51] studied the effect of sonication on viscosity and thermal conduction. For viscosity, a cone-plate viscometer was used, which observed that the longer the exposure time, the lower the viscosity and the greater the thermal conductivity.

3. Stability of Nanofluids

The low stability of nanofluids over prolonged periods and their proneness to agglomeration have made their use on a large scale difficult. The nanofluids can lose their capacity to transfer heat and have their thermophysical properties altered due to the sedimentation [52]. The fast sedimentation of these colloidal suspensions of nanoparticles in a base fluid can also cause problems related to viscosity and flow in channels with complex geometries, mainly in microchannel systems [53]. Traditional techniques are used to solve the problems related to the stability and sedimentation of nanofluids. The most common are: the addition of surfactants, ultrasonic vibration, and controlling the pH value of the suspensions. In addition, new techniques have been presented to improve the stability of nanofluids and increase heat transfer [54]. In this work, the authors compare two distinct fluids; one formed by a traditional NF containing Al_2O_3 nanoparticles, and the second a novel NF formed by polyacrylic acid (PAA)-coated iron oxide nanoparticles (Fe_3O_4@PAA), obtained from a hydrothermal synthesis route. The results showed levels higher than the stability for the NF produced by the hydrothermal synthesis process.

The option of adding surfactants to the nanofluids can be seen in several literature works [55–57]. The stabilization of nanofluids is achieved by reducing surface tension and increasing the immersion of particles in the base fluid [52]. However, the use of surfactants has some disadvantages. It interferes with the thermal properties of nanofluids compromised by increasing thermal conductivity, creating thermal resistance during the flow [58–60]. When heated at high temperatures, it can generate foams [58,59], which when used during the nanoparticles' synthesis prevents their clustering only for a certain period of time [2,61].

Ultrasonic vibration is an efficient method to break down agglomerates of nanoparticles, making the mixtures more homogeneous. The dispersion level of nanoparticles in the base fluids will depend on the duration of the sonication process. Another important effect is that the size of the nanoparticles can change with the sonification time, and for this reason, more studies are needed. For example, using Au-water nanofluids, Chen and Wen [62] evaluated the effect of sonification time (from 10–60 min) on the particles size present in the nanofluids. The results obtained showed a decrease in particle size up to 45 min after beginning the process, while after that, no reduction was observed. The thermal conductivity is also affected by the dispersion of nanofluids and consequently has a direct impact on heat transfer. In the work of Saidur et al. [2], they revealed that the nanofluids produced more recently exhibit slightly higher thermal conductivities than those stored up to two months.

The effect of pH on the properties of nanofluids is directly related to the electrostatic forces of interaction between particles dispersed in the base fluid. If the repulsion force between the particles is great, the colloidal mixture tends to stabilize through the high surface charge density generated [58]. In addition, when repulsive forces increase, particles can move freely due to Brownian motion, thus facilitating thermal transport [63]. However, if the electrostatic force is weak, the particles are attracted to each other, causing them to agglutinate and become sediment. Figure 1 shows several parameters that may affect the stability of nanofluids.

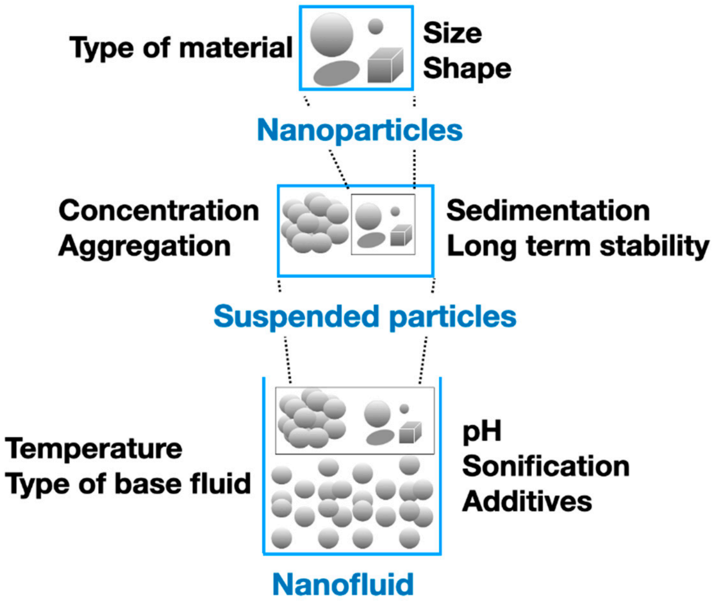

Figure 1. Different features that may affect the stability of nanofluids, adapted from [37].

4. Nanofluid Application in Machining

The cutting fluid has three main functions in metal cutting operations: lubricates the tool/workpiece interface, cools the workpiece surface and the cutting tool, and removes the chips from the cutting from the cutting region. The use of cutting fluids during machining enables the economy of tools, provides tight tolerances, and improves and protects surface properties from damages [64]. Nevertheless, the use of cutting fluids negatively affects human health and the environment, both through their use and their disposal [65]. As well, the cutting fluid occupies 16–20% of the cost of production in the manufacturing industry. Therefore, excessive use of cutting fluids (flood lubrication) should be limited [66] and substituted by dry machining or minimum quantity lubrication (MQL), which can be adopted to spray cutting fluid over the tool/workpiece interface [67]. The MQL is also known as clean manufacturing [68]. There is a classic classification that indicates three types of cutting fluids: neat cutting oil, water-soluble fluids, and gases [69]. The most used are the water-soluble fluids in which it is possible to add nanoparticles, thus obtaining the nanofluids. The nanofluid is a colloidal mixture of nanometer-sized, smaller than 100 nm, metallic and non-metallic particles in conventional cutting fluid [70]. This new class of cutting fluids can be synthesized by mixing metallic, non-metallic, or carbon nanoparticles in a conventional cutting fluid which compared to the isolated fluid with the nanofluids shows better stability, good thermal conductivity, rheological properties, and no effect on pressure drop [71]. Nanofluids possess a high level of heat extraction capabilities (thermal conductivity) over conventional cutting fluids [2,72]. Some researchers concluded that this enhanced thermal conductivity might be an important factor for better performance in various applications [2]. The ratio of surface area and volume of nanoparticles is the main factor that influences the thermal conductivity of nanofluids [73] and it was also discovered that the thermal conduction increased with the growth of particle concentration and with decreasing particle size [74]. Aside from thermal conductivity, the friction between workpiece and tool can be a crucial element to generate high temperature at the cutting region, which affects the surface quality, the workpiece dimensional accuracy, and the tool life during the cutting process. Lee et al. [75] observed that the addition of graphite nanoparticles increases the lubricating property of standard lubricants because it lowers the friction coefficient. Because of their low friction behavior, the graphite and MoS_2 solid lubricants can reduce the surface roughness and decrease the cutting force in the machining process [76].

Nanofluids are potential facilitators to reduce cost, improve tool life, and optimize the machining process. The most common machining processes in which nanofluids are used are turning, milling, drilling, and grinding. In former years, different formulations have been developed for all these machining processes. Regarding turning, Rahman et al. [77] employed two kinds of formulated nanofluids to machine Ti-6Al-4V ELI, and concluded canola-based Al_2O_3 nanofluid with loading concentration of 0.5 vol.% led to lower surface roughness. For the high-speed turning process, Roy et al. [78] used 3 vol% of alumina and 1 vol.% of MWCNT, resulting in a severe reduction of cutting force and specific energy. Still, MWCNT presents better efficiency related to cutting zone temperature and tool life. Sharma et al. [79] evaluated the effect of utilizing an Al_2O_3–graphene nanoplatelets hybrid nanofluid as the cutting liquid on the tribological features in turning of AISI 304 steel. Adding the graphene nanoplatelets to the Al_2O_3 nanofluid increased the tribological characteristics. Figure 2 illustrates the mechanism of nanoparticles entrapped between the sliding surfaces.

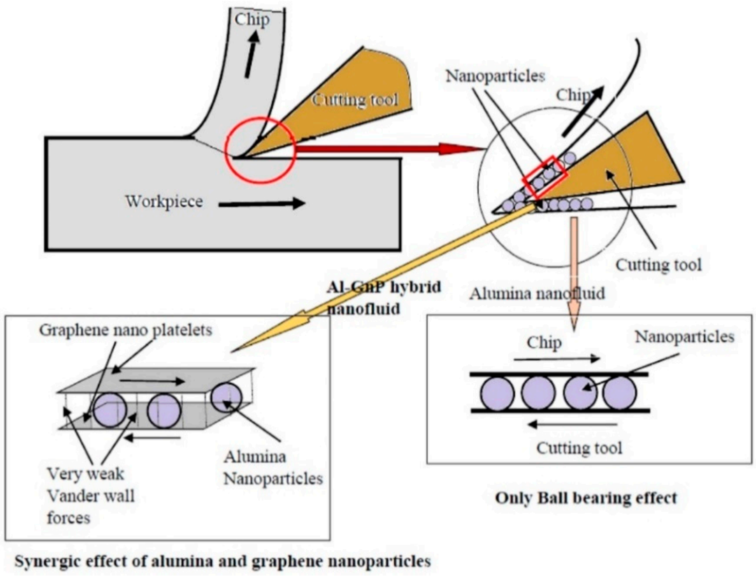

Figure 2. Synergic influence of the Al_2O_3 and Al_2O_3–graphene nanoplatelets trapped between the sliding surfaces. Reprinted with permission from Ref. [79]. 2018 Elsevier.

Recently, the MQL system was adopted for the application of a developed nano lubrication system to the cutting zone. Less nanolubricant consumption is a beneficial aspect of using pressurized air to accelerate the addition of nanolubricant into the tool/workpiece interface. Using nanolubricant in the milling process helped achieve high-quality machined surfaces due to the presence of applied nanoparticles. Rahmati et al. [80] examined the impact of the MoS_2-based nanolubrication system on the machined surface morphology using the MQL system. These authors verified that a developed MoS_2-based nano lubrication system is beneficial for accomplishing high surface quality. Jamil et al. [81] investigated the key machining characteristics during the milling process of Ti-6Al-4V accompanied by applying a hybrid nanofluid (Al_2O_3-MWCNT). The authors proved that using hybrid nanofluid leads to attaining better performance related to tool wear that results in a reduction of energy consumption. A successful drilling process is frequently determined by the efficiency of the employed drilling fluid. Drilling fluids can control surface pressure, prevent contamination, and function as lubrication [82]. Huang et al. [83] created a novel nanofluid/ MQL technology for microdrilling. They showed that the created nanofluid/MQL with a loading concentration of 2 wt.% could achieve an attractive microdrilling force and microdrilling torque, as well as increase drilling quality due to a substantial decrease in the drilling process. The grinding process is important in materials removal operations, particularly if it is required to reach close tolerances. Formulated novel nanofluids can substitute traditional cutting fluids to increase the quality of the grinding process, lubrication, and surface finish. Lee et al. [84] formulated and used a novel ND-based nanofluid associated with the MQL technique in the grinding process. They reported a considerable decline of 33.2% in normal components, while the developed reduction in tangential components was reported as 30.3%. The surface roughness measurement resulted in a considerable decrease of 64% due to the presence of used nanoparticles.

In a machining process, four main characteristics must be controlled: surface roughness, cutting force, tool wear, and tool life in which the nanofluids could have an important role [68]. Required surface quality is one of the key factors in the machining process. This surface quality can be evaluated by the surface roughness, which is a technical requirement for most mechanical products [85]. The utilization of nanofluids as a substitution of conventional cutting fluids has improved the quality of products by decreasing their surface roughness. So, the reduction of surface roughness could go from 8.72% using Al_2O_3 with carbon nanotube (CNT) in vegetable oil [86] to 47.8% with aluminum oxide (Al_2O_3) with vegetable oil [87]. The cutting force is a very important parameter directly related to the cost-effectiveness of parts, so high-level cutting force demands raised values of power consumption and, consequently, the machining costs increasing. Some research works showed a significant decrease in cutting forces when nanofluids are used. This diminution can contain up to 50% aluminum oxide added to the conventional cutting fluid [88]. However, opting for a more environmentally friendly choice, it is also possible to reduce 37% in cutting forces by applying coconut oil (CC) associated with nano molybdenum disulfide ($nMoS_2$) [89]. Tool wear is mostly related to cutting conditions [90], and various types of tool wear occur during the machining process, such as crater wear, notch wear, chipping wear, comb crack, and, most commonly, flake wear [91,92]. The crater wear is mainly due to diffusion and abrasion, and the diffusion is activated mainly by high temperatures, so if we decrease the temperature in this region, we consequently decrease crater wear. The notch wear is caused by mechanical abrasion from harder workpieces which, in the same way as crater wear, occurs due to hard particle diffusion, influenced again by temperature. The flank wear is the most important wear that appears on the flank surface parallel to the cutting edge. Generally, it generates high temperatures, which affect tool and work material properties. Another indirect influence of temperature in the tool wear is due to the thermal expansion of materials (tool and workpiece) that occurs at high temperatures. This phenomenon causes high contact pressures between the workpiece and the tool and, as a result, promotes an increase in tool wear. To minimize the aforesaid drawback, several researchers have applied nanofluids to improve the thermal properties. Thus, it is possible to reduce tool wear meaningfully using nanofluids, as proved by Zhou et al. [93], who used Fe_3O_4 with conventional coolant to improve the wear resistance up to 63% for crack wear on the rake face. Following the same goal line, Eltaggaz et al. [94] developed a formulation of Al_2O_3 with vegetable oil to reduce the flank wear up to 26.5%. In this sense, Vázquez et al. [95] tested CuO nanoparticles with mineral oil and achieved an increased service life of the cutting tool up to 604%. In other research work, Minh et al. [96] used Al_2O_3 with soybean oil and verified that tool life increases almost 177% over the base fluid.

5. Solar Panels and Collectors

Photovoltaic solar panels are devices capable of converting solar energy into electrical energy. These panels are formed out of photovoltaic cells that need sunlight for their operation. However, an excess of solar energy causes high temperatures on the surface of the cells, impairing the functionality of these systems. The problems with the high environmental temperatures from some regions of the globe have led to the development of alternative cooling techniques. The performance of the output power of a photovoltaic module decreases by 0.4% to 0.5% per 1 °C when it works above its ideal temperature, in most cases being 25 °C [97]. To avoid the overheating of PV modules, nanofluids are potential candidates for cooling these systems. Ebaid et al. [97] using two types of nanofluids, Al_2O_3 and TiO_2 mixed in water, for different volume flow rates and concentrations of

0.01%, 0.05%, and 0.1% by weight, the authors evaluate the performance of heat transfer for three PV panels cooled simultaneously using nanofluids, water, and natural air. Results obtained showed that nanofluids enhanced heat transfer rate much better than water or natural air.

The interest in nanofluids is due to their possibility to change the transport properties of the base fluid with the presence of suspended metallic or non-metallic nanoparticles when compared to conventional heat transfer fluids [2,98]. In the solar energy area, the applications of nanofluids can be found, for example, in photovoltaics thermal systems and thermal energy storage [99]; solar collectors, solar stills, and hydrogen conversion (fuel cells) [100]. Several researchers have shown that the thermal conductivity of nanofluids increased as a function of nanoparticles volume concentration and temperature [101–104]. Regarding the increase in thermal conductivity with temperature, this characteristic of nanofluids can positively benefit the cooling of the modules. However, the increase in volumetric concentration, which on the one hand benefits the increase in thermal conductivity, on the other hand, can raise the viscosity of nanofluids to levels that impair pumping capacity and increase the pressure drop of the systems. The problem with the pressure drop was related in experiments under the laminar flow regime [105] as under a turbulent regime [106], where there was an increase in power pumping with the increase of the volume fraction of nanoparticles in base fluids.

Most studies reported in the literature have evaluated the use of serpentine heat exchangers using nanofluids to cool solar photovoltaic/thermal systems (e.g., [107,108]). These studies show that the nanoparticles added to the base fluid have enhanced the heat transfer and reduced the operating temperature of the panels. For example [108], concluded that the utilization of water/magnetite nanofluid with 2% volume concentration possesses the highest ability for being employed as a cooling fluid compared with the NF volume concentration of 0% (pure water), 0.5%, 1%, and 1.5%, respectively. Hussien et al. [109] conducted an experimental investigation for improving a hybrid photovoltaic/thermal system performance using a nanofluid (Al_2O_3-Water) by applying forced convection for different concentrations, from 0.1 to 0.5%. The results showed that for a concentration of 3% the temperature dropped significantly to 42.2 °C and the electrical efficiency rose to 12.1%. However, increasing the concentration for more than this value caused a raising of the temperature to 52.2 °C while the electrical efficiency declined to 11.3%. An example of using nanofluids in serpentines for cooling photovoltaic solar panels can be seen in Figure 3.

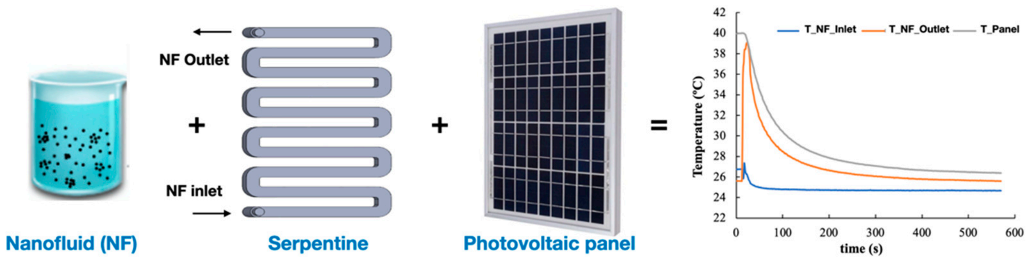

Figure 3. Scheme illustrating the use of nanofluids in serpentines for cooling photovoltaic solar panels.

Singh Rajput et al. [110] conducted an experimental investigation to analyze the performance of a flat plate solar collector using Al_2O_3/Distilled Water Nanofluid. The Al_2O_3 concentration varied from 0.1, 0.2, and 0.3% by volume, and the dispersion quality of nanoparticles in the fluid was enhanced using 0.8% wt. of surfactant sodium dodecyl sulfate (SDS). Singh Rajput et al. [110] report that the nanofluid at a volumetric concentration of 0.3% presented a maximum increase in collector efficiency of 21.32%. Michael and Iniyan [111], using CuO/Water nanofluid prepared at a low volume concentration of 0.05%, obtained an increase in the thermal performance of the solar water heater by 6.3% considering a flow rate of 0.1 kg/s. Colangelo et al. [112] performed an experimental investigation to evaluate the problem of sedimentation particles through a flat plate solar collector operated with nanofluids. The NFs tested were Al_2O_3, ZnO, and Fe_2O_3 with different shapes and concentrations of the 1 vol%, 2 vol%, and 3 vol%. They concluded that flow velocity is the principal factor affecting particle sedimentation. Furthermore, they concluded that the thermal conductivity enhancement up to 6.7% at a concentration of 3 vol% of Al_2O_3, while the convective heat transfer coefficient increased up to 25%.

Phase Change Materials (PCM) are another kind of materials used for solar thermal applications, which can help to solve part of the intermittency problem of solar energy and increase the daily thermal energy storage efficiency of solar thermal applications, such as solar power plants [113]. One of the authors' conclusions is that the dispersion effect of nanoparticles is the basic starting point of thermal conductivity enhancement of the PCMs, and is responsible for ensuring that energy is stored and released well during the flow.

The thermal absorption performance of nanofluids is another important characteristic of this colloidal mixture. Recently [114], an experimental study was performed to evaluate the thermal absorption performance of nanofluids of carbon nanotubes, Cu, and Al_2O_3 using water with base fluid. The authors show that all nanofluids increased the absorbance and electrical conductivity with increasing nanoparticle concentration, which has improved the thermal absorption performance of nanofluids. Depending on the amount of absorption and the energy transferred by the fluid during the process of capturing solar energy, the solar energy efficiency can vary widely [115]. Furthermore, according to Sidik et al. [116], due to their ability to change the working fluid properties, such as light absorption and thermal conductivity, nanofluids are considered the best option for solar collector applications.

Proposed by Minardi and Chuang in the 1970s [117], direct absorption solar collectors (DASCs) emerged as a promising way to reach high thermal efficiency. In these devices, the solar irradiation is absorbed by the fluid, where it works as an absorber and a heat transfer medium at the same time [118]. In these collectors, heat loss to the environment is reduced as high temperature occurs in the fluid. Hence, the efficiency of DASCs will be greatly dependent on the thermal characteristics of the working fluids. Fluids having high thermal conductivity, excellent optical absorption, and good photo-thermal conversion performance are highly desirable for developing high-efficiency DASCs [118].

Chen et al. [118] have tested reduced graphene oxide (RGO) nanofluid prepared by irradiating a graphene oxide (GO)/water one under UV light for different times. They have experimentally evaluated the photo-thermal conversion performance of one DASC. The results have shown that the RGO/water nanofluid prepared from the GO/water one shows great potential to be used as a working fluid in low-temperature direct absorption solar collectors due to the good stability along with the high optical absorption and thermal conductivity presented. The RGO/water nanofluid exhibited superior photo-thermal conversion efficiency to the GO/water and graphene (GE)/water ones at the same loading, which reached 96.93% at 30 °C and 52% at 75 °C.

In 2017, Ahmad et al. [22] showed that most studies involving nanofluids have focused on their thermal properties, and only a small portion of the studies have evaluated the contribution of optical properties to solar thermal applications. Optical properties such as absorption, transmittance, scattering, and extinction coefficient have been investigated, however, for more comprehensive conclusions, further studies will be needed. For example, in work presented by Ahmad et al. [22], they reported several divergences such as:

- the optical solar absorption increased accordingly with increasing nanoparticle size and volume concentration;
- the path length has some remarkable effects over optical absorption of nanofluids;
- the transmittance of nanofluids has indirect relation with nanoparticle size, volume fraction, and path length;
- the scattering of light is directly proportional to the volume concentration and particle size of metallic particles;
- the presence of large particles and agglomeration of particles leads to a significant amount of light scattering, and as a result, the overall extinction coefficient will be increased.

It is normal for the literature studies to verify that the enhanced thermal conductivity of NFs is the principal factor that improves the general efficiency of solar systems. However, other effects are completely disregarded from the studies, such as: (i) the distribution of the absorbed solar energy within the nanofluid to eliminate any peak temperatures and consequently minimize heat loss to surrounding [100]; (ii) the effect of pressure drop mainly due to the increased concentration and viscosity of nanofluids; (iii) development of inexpensive NPs production techniques is crucial. There are few experimental studies on solar systems concerning solar thermoelectric cells, solar ponds, parabolic trough systems, and photovoltaic thermal systems, so more studies are essential to confirm the performance of these systems using NFs.

6. Biomedicine

In the biomedical field, different types of nanoparticles (NPs) have been developed to improve the diagnosis and treatment of several diseases. Their small dimension makes them suitable to travel through the bloodstream and interact with cells. They have also shown biocompatibility, high charge carrier mobility, high surface-to-volume ratio, and high physicochemical stability [119,120]. Consequently, by modifying their shape, size, charge, and surface functional groups, the NPs can be loaded with drugs or biomarkers and specifically target certain cells or release the loaded drug in a controlled fashion. The surface-area rate of the NPs is greater than the rate of macroparticles. Subsequently, they allow the incorporation of greater quantities of drugs, targeting agents or biomarkers, to have more area of contact with the cells [121]. Endogenous stimuli, such as pH or enzymes, exogenous stimuli, alternating magnetic fields, or near-infrared light, can also be used to control the drug release [122]. Some NPs have also shown antibacterial or anticancer properties on their own [123,124], and some also can serve as a diagnostic or monitorization tool. Due to such properties, NPs have been explored to optimize the treatment of severe diseases such as cardiovascular and neurodegenerative conditions and cancer [125–128].

The main objectives for the development of nanomaterials for cancer treatment applications are [121]:

- Reduction of toxicity and side effects of conventional drugs by increasing their efficiency;
- Specific binding to target cells;
- Improvement of solubility, stability, tumor aggregation, and half-life of conventional drugs;
- Release of the loaded drug through a stimuli-responsive mechanism;
- Increase the area of interaction for encapsulated drugs or drugs attached to biomacromolecules;
- Overcoming drug resistance by delivering several active agents to specific cellular target sites;
- Overcoming biological barriers;
- Improvement of diagnostic and imaging sensitivity;
- Assessment of drug efficiency in real-time by linking imaging molecules and active anticancer components;
- Contribution to the development of new vaccines;
- Improving the diagnostic and imaging of cancer using smaller devices.

Tumor sites are usually poorly vascularized regions. NPs tend to accumulate on the tumor site and increase the retention effect and the permeability, which helps enhance cancer treatments. However, several biological processes can influence the NPs action. Consequently, the features of the NPs, such as dimensions, structure, surface properties, shape, and porosity, must be controlled to achieve the ideal interactions [121]. For instance, one strategy can be reducing the size of the NPs so that they can cross the leaky tumor vasculature but leave them big enough to not leak from the healthy blood vessels. The shape of the NPs affects the uptake of the particles by the cells. However, most studies have used spherical-shaped particles due to challenges in synthesis. The surface chemistry also needs to be carefully engineered considering the type of tumor cells that will be targeted. Some studies indicated that positively charged surfaces increase cellular uptake. However, some studies reported the preference of neutral or negatively charged surfaces for some types of cancer [121]. Drugs are conventionally administered by injection or oral intake. Those pathways have several limitations, such as limited effectiveness and lack of selectivity. For instance, orally taken drugs have poor biodistribution and variable absorption. They can also suffer degradation by the gastric acidic environment together with digestive enzymes [129]. Some anticancer drugs, such as paclitaxel, are not soluble in water which can be overcome by loading the drug onto NPs. Another problem with cancer drugs is the fast elimination through the renal system. NPs can also contribute to enhancing the half-life of the blood circulation of drugs. Encapsulation of the drugs also contributes to protecting them against metabolic degradation [121].

One recent cancer treatment technique is hyperthermia, and it corresponds to a treatment where body tissue is subjected to high temperatures due to an external source. Research on this technique has been increasing over the last decades. Some procedures included warming up the patient's blood on an external device and then retransfusing it. Hyperthermia treatments are also performed by applying the heat generated by electromagnetic waves directly on the tumor region with the guide of imaging techniques or to the whole body in case of the presence of distant metastasis [130]. To increase the specificity of hyperthermia treatments and reach deeper tumor sites, magnetic NPs were developed. The most common NPs used in this technique are iron oxide-based NPs due to their superior magnetic properties. To reach an effective treatment, the NPs should present a super-paramagnetic behavior that increases with the size of the particles. However, the NPs should not be too big to flow continuously through the blood capillaries and penetrate the tumoral tissues. The surface of the magnetic NPs is usually functionalized to improve the stability and resistance of the particles to the surrounding physiological environment. Drugs or specific cellular markers can also be incorporated for combined therapy and specific targeting [131,132]. In this procedure, magnetic NPs are administrated to the patient, and an external alternating magnetic field is applied to the tumor site. The heating is generated by the particles due to hysteresis losses or other displacements of the domain wall. However, for super-paramagnetic particles, the heating is generated by the losses that occur during the reorientation of the magnetization [130]. The generated heat can induce cancer cell death through coagulation, denaturation, folding, and aggregation of proteins, apoptosis, and necrosis, or by promoting the overexpression of heat shock proteins, among other processes. Characteristics of the NPs, such as specific absorption rate and magnetic properties, and of the applied magnetic field will influence the effects of the technique. The hyperthermia treatment can be combined with chemotherapy and radiotherapy treatments for increased treatment efficacy [133,134].

NPs from organic materials, such as proteins and lipids, were studied for cancer treatment applications due to their biocompatibility and biodegradability. Nevertheless, those NPs are not as efficient and versatile for drug delivery as the NPs from inorganic materials, such as gold, silver, iron, or zinc oxides [135]. On the other hand, further research of the effects of the NPs circulating on the human body is still required. Not only is it important to analyze the effect on the healthy organs that are not the target of the treatment, but also to analyze the blood cells. Rodrigues et al. [136] evaluated the effect of MNPs on the red blood cells (RBCs), as presented in Figure 4. The authors reported a slight increase in the RBCs' rigidity when in the presence of MNPs.

The combination of microfluidics and cell culture on devices such as the organ-on-a-chip also brings forth the possibility of a dynamic evaluation of the systemic effects of the NPs on the human body [119,123,137,138].

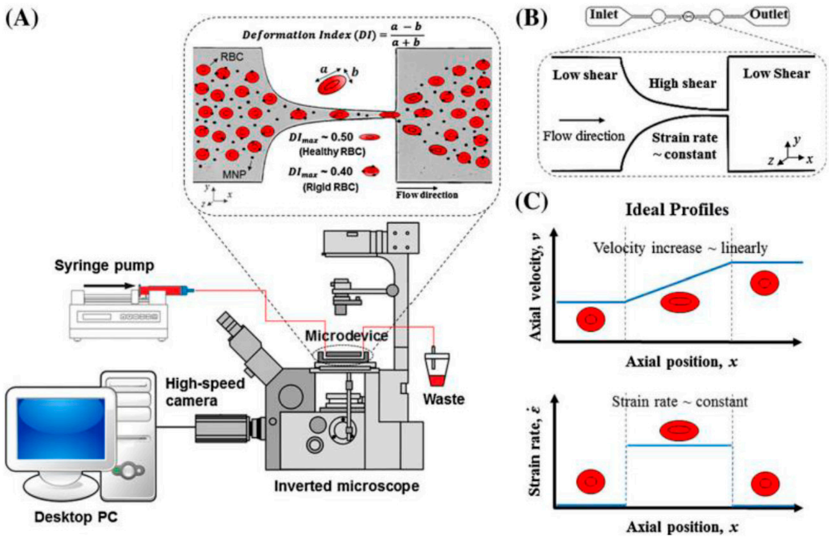

Figure 4. Schematic representation of NPs hemocompatibility evaluation. (**A**) Experimental setup. (**B**) Microchannel geometry. (**C**) Condition profiles present in the hyperbolic channel. Reprinted from [136]. 2016 Springer Nature.

7. Conclusions

This review shows an overview of the NFs benefits applied in three specific areas: machining, solar energy, and biomedical engineering.

- In the machining area, the use of NFs has helped to obtain high-quality machined surfaces, has improved tool life, and reduced costs in all branches of the sector, namely in turning, milling, drilling, and grinding.
- In the area of solar energy, NFs have been evaluated in heat exchangers for cooling solar systems. The results have shown that nanoparticles added to the base fluid increase heat transfer and reduce the operating temperature of the panels. Furthermore, due to the superior thermal absorption performance of the nanofluid, it has been used to improve the efficiency of capturing solar energy in direct absorption collectors.
- In the biomedical field, the use of the NFs has helped improve the diagnostic and treatment of several diseases.

Due to the superior thermophysical properties of these colloidal mixtures, the number of studies and interest in the subject has grown massively in recent years. If, on the one hand, there is a consensus regarding its thermal transport capacity due to its higher thermal conductivity compared to base fluids, on the other hand, a list of problems has limited large-scale applications. However, this review sought to highlight studies that inspired solutions to overcome these challenges.

Advantages of nanofluids:

- NFs can have their properties adjustable depending on the concentration of nanoparticles used, including the increase of thermal conductivity in relation to their base fluids being the main attraction for most applications;
- The heat transfer from the NFs presents higher values in relation to the respective base fluids, due to enhancement specific surface area between nanoparticles and liquid;
- Some results from the literature have shown a significant increase in thermal conductivity when an extremely low concentration of NPs was used, reducing production costs.
- The nanoparticles in the base fluid change the optical properties of the NF, benefiting light absorption for applications in solar collectors.
- Many kinds of nanoparticles can be used to form NFs, such as metallic, with magnetic properties; or non-metallic, as used in cancer theranostics.
- Disadvantages of Nanofluids:
- The low stability of NFs for long periods of time and their rapid sedimentation;

- The effects of ultrasonic vibration, the addition of surfactants, and control of the pH value of NF suspensions are still poorly understood;
- The two main techniques for obtaining nanoparticles need to be improved. One is too expensive (one-step), and the other (two-step) does not favor the stability of NFs;
- Enhancement of the pressure drop in systems that require pumping due to the increased viscosity of NFs.

During the last decade, several solutions have been proposed to overcome the NFs limitations. An alternative to solving the problem of the low stability of NFs is by modifying the surface of the nanoparticles before forming the NFs. Hence, NPs surface modification can contribute to an increase of the electrostatic force between the NPs, preventing them from agglomerating and, as a result, may reduce sedimentation. Encouraging results have been achieved by new NP production techniques, such as the hydrothermal synthesis process shown in this review.

A general trend of NFs is that viscosity decreases with increasing temperature and decreasing concentration of NPs. For this reason, regarding pumping systems that are subject to high temperatures, NFs should be an effective option. Another interesting approach is the use of magnetic NPs under the influence of magnetic fields to prevent the sedimentation of NPs. To overcome the high costs associated with the production of NPs, one possibility is by using recycled and recovered NPs from industrial wastes.

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