The Role of Nanofluids in Enhancing Energy Conversion Technologies: A Comparative Study of Different Types of Nanoparticles

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Abstract: The integration of nanofluids into energy conversion systems has emerged as a promising strategy for enhancing heat transfer performance and overall efficiency. This study provides a comparative analysis of different types of nanoparticles—including metal oxides, carbon-based nanomaterials, and hybrid composites—dispersed in base fluids to evaluate their impact on thermophysical properties such as thermal conductivity, viscosity, and specific heat capacity. Experimental and computational investigations reveal that nanofluids significantly improve heat exchanger performance, solar thermal collectors, and cooling systems by facilitating superior thermal transport mechanisms. However, variations in stability, cost, and environmental impact across nanoparticle types necessitate careful material selection for specific applications. The findings underscore the importance of optimizing nanoparticle concentration, size, and morphology to achieve maximum efficiency gains while mitigating potential operational challenges. This comparative study aims to inform the development of next-generation energy conversion technologies that are both efficient and sustainable. Studies on nanofillers show that the increase in the thermal conductivity of nanofluids depends on many variables, including the size of the nano-shaped filler and the surface area of the particle, the amount of filler, particle aggregation, viscosity stability, Brownian motion, and the temperature effect. This article introduces these factors and how they affect the heat transfer of nanofluids.

Keywords: Nano fluids, Energy conversion ,Heat transfer enhancement ,Nanoparticles ,Thermal conductivity ,Comparative study ,Hybrid nano fluids, Heat exchangers ,Solar thermal systems ,Thermal management

1.Introduction

Given the importance of energy issues worldwide, increasing the rate of heat transfer by industrial equipment and thus reducing energy loss is a very important issue in this regard. That is why thermal management is considered a critical factor in the optimal performance of devices or machines and also in increasing their useful life. Cooling systems for electrical devices have always been one of the most important concerns of factories and industries that deal with heat transfer in some way. In most cases, optimization of existing heat transfer systems such as fans has been done by increasing their surface area, which generally increases the volume and size of these devices.

In addition to cooling fans, in some systems, water-oil fluids (....) are also used to dissipate heat generated by coils and other factors, but the rate of heat transfer by these fluids is very low due to their low thermal conductivity. Therefore, new and

effective coolers will be needed as a suitable solution in this field to overcome these problems.[1]
Nanofluids, which are obtained by distributing nano-sized particles in conventional fluids, are a new generation of fluids with very high potential in industrial applications. These particles can be made of metallic nanoparticles (copper, silver, etc.), metal oxide nanoparticles (aluminum oxide, copper oxide, etc.), carbon nanotubes and nanoplates (graphene nanotubes), and non-metallic nanoparticles (boron nitride, etc.) Due to their high thermal conductivity, nanoparticle increases the thermal conductivity of the fluid after distribution in the base fluid. The results of experiments conducted on several nanofluid samples regarding the heat transfer method show that the performance of nanofluids in heat transfer is generally higher than what is theoretically predicted .[2]

2.nanofluids For Providing fluids with improved cooling capabilities

Cooling fluids are used in many industrial fields such as electronics, refrigeration, air conditioning, and transportation. The thermal conductivity of these fluids plays a vital role in the development of high-efficiency heat transfer devices. Since solids have much higher thermal conductivity than conventional fluids, the idea of introducing thermally conductive particles into the fluid was considered more than a century ago by James Clerk Maxwell ,He used millimeter or micrometer particles and, by dispersing them in conventional fluids, presented a method for calculating the effective thermal conductivity of the resulting suspension. This method was later investigated by Hamilton and Crosser and applied to particles of various shapes and compositions .
However, none of them succeeded in predicting the enhanced thermal conductivity of nanofluids because their models did not include any dependence on particle size. The use of millimeter or micrometer particles in early studies caused numerous problems.[3]
The most important of these was the rapid settling of particles, which not only did not increase thermal conductivity, but also led to the formation of sludge deposits, increased thermal resistance, and impaired the heat transfer capacity of the fluid.[4]

Table 1 shows the thermal conductivity of conventional fluids and metallic, non-metallic, and carbon solids.

Heat transfer using fluids is a very complex phenomenon, and various factors such as fluid stability, composition, viscosity, surface charge percentage, and morphology of dispersed particles affect the final results , Optimization of the aforementioned factors and, as a result, high efficiency of components and devices is very important, because these factors play an important role in various fields such as microelectronics, engines, fuel cells, air conditioning, power transmission systems, solar cells, medical treatment and diagnosis, biopharmaceuticals, etc.
In line with the above explanations, researchers used nanotechnology to eliminate the defects of fluids containing micro (milli) particles and achieve a desired fluid with the desired properties.[5]Therefore, in this regard, nanofluid

technology was presented as a new option in line with the studies of heat transfer fluids, and various review articles were published in this field When crystalline solids with nanometer dimensions are dispersed in the desired fluid to prepare a stable homogeneous suspension and the thermal conductivity of the resulting fluid is higher than that of the pure fluid, the suspension is called a "nanofluid".

and by combining nanotechnology and thermal engineering, nanofluids are a class of solid-liquid composite materials containing solid nanoparticles in the range (1100) dispersed in a heat transfer fluid such as ethylene glycol, water or oil.

The study of nanofluids is increasing and reached about 1400 authoritative scientific articles in 2015. Today, nanofluids with higher thermal conductivity than the base fluid for cooling and heat dissipation not only increase the useful life of components but also lead to a desirable reduction in energy loss, which is of particular importance. [6]
Therefore, the emergence of heat transfer systems based on nanofluids improves the thermal, physical and electrical properties of devices, since achieving the technical knowledge of preparing nanofluids with a minimum concentration of filler that does not increase the viscosity of the fluid and at the same time shows a desirable thermal conductivity is important. Many studies have been conducted on new nanofillers and how to prepare related nanofluids that can increase the thermal conductivity of the fluid in exchange for a small percentage of filler .

It should be noted that in some cases, surface modification reactions are carried out on the nanoparticles to improve the dispersion of nanoparticles in the fluid and also to increase the stability and properties of the desired fluid.[7]

3.Nanofluids Heat Transfer Variables and Properties

The increase in thermal conductivity of nanofluids depends on many variables that cause different properties to emerge in these materials. These are mentioned below.

1.3. Nano filler size

Various studies have shown that the smaller the size of nanoparticles, the higher their effective thermal conductivity. This is due to their Brownian motion Also, lighter and smaller nanoparticles resist sedimentation and fouling, which is one of the biggest technical challenges in most nanofluids In this regard, Mortazavi et al. studied the effect of particle size on the thermal conductivity properties of crystalline BN sheets using molecular dynamics simulations They prepared large atomic models of polycrystalline BN sheets with uniform and random configurations. The results of their research not only provided a general perspective on the thermal conductivity of BN films, but also showed that polycrystalline BN sheets have higher thermal conductivity compared to single-crystalline BN sheets.

2.3. Particle shape Surface area

Many studies have shown that rod-shaped nanoparticles such as carbon nanotubes have a higher heat transfer coefficient compared to spherical nanoparticles [16], which is due to the larger aspect ratio of the surface area of a particle to its volume. For different BN structures, the results show that BN nanoribbons have a higher thermal conductivity (2000-1700 mk) than nanosheets (100-1000 mk) and nanotubes (660 mk) .[8]

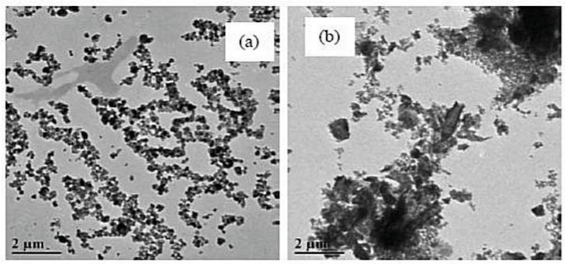
3.3- Amount of filler

Probably, the main factor in improving thermal conductivity is related to the concentration of nano-filler dispersed in the fluid. The effective thermal conductivity of nanofluids increases with increasing filler content, but it should be noted that increasing the filler percentage makes it unacceptable to consider the term nanosuspension to the aforementioned nanofluid. It will also lead to a drop in fluid flow pressure. This is why the use of filler at low percentages will be much more effective. At low filler percentages, nanostructures have more Brownian motion at high temperatures, which will significantly increase Kerr. In contrast, at higher filler percentages, nanoparticles tend to aggregate at high temperatures. 20) In the case of nano-BN systems, thermal conductivity will also increase with increasing filler percentage in the fluid.[9]

3-4- particle accumulation

A major challenge with nanofluids is that nanoparticles tend to aggregate due to molecular interactions such as van der Waals forces 20, 21 . Therefore, particle aggregation increases with increasing filler percentage.[10]

Also, the viscosity of the system increased and with decreasing the effective surface area to volume ratio, the thermal performance of the fluid also decreased. In a study, h-BN powder nanoparticles were used as fillers in ethylene glycol fluid. |22 After preparing nanofluids with filler amounts of 0.02.01 and 0.2751 and investigating their thermal conductivity properties, the results showed that the thermal conductivity for the nanofluid with 0.025701 filler was higher than the other. According to the high-resolution transmission electron microscope (HRTEM) images and the morphology of the nanofluids in Figure (1),

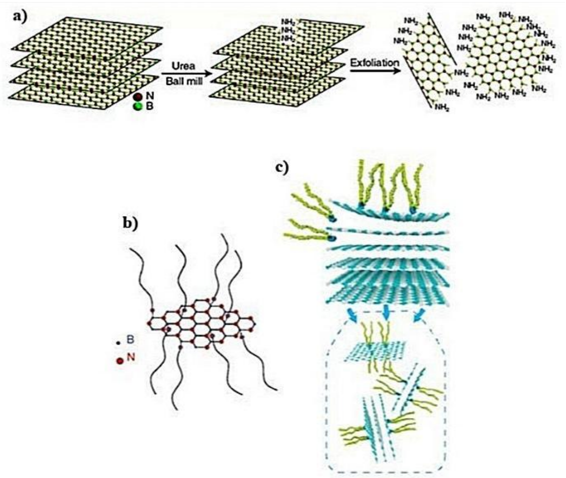


they found that at a lower percentage, the particles were in the form of weak chain-like aggregations as a dense three-dimensional network and were thermally conductive, while for Higher percentages, dense cloud-like accumulations and reduced heat transfer paths are observed.

5-3- Sustainability

Stability means that particles do not aggregate at a significant rate. Generally, the rate of aggregation is determined by the collision frequency and the probability of coalescence during collision. There are two mechanisms in this regard (1) electrostatic stability (2) spatial stability[11]

Electrostatic stability The presence of an electric charge on the surface of the particles will lead to their kinetic stability. In a study, stable aqueous colloidal nanoplates were prepared through a chemical mechanical process by creating amine groups on the surface of the nanoplates (Figure (2)).



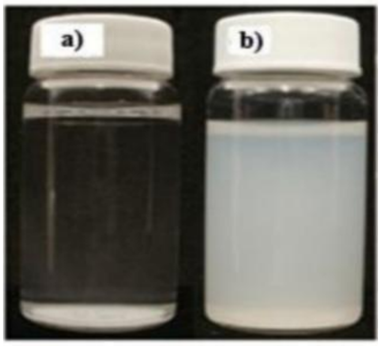
The zeta potential for the initial boron nitride in water was 47, which is not able to disperse well in the aqueous phase due to the hydrophobicity of boron nitride and its large particle size. After modifying the nanoplates with amine groups, the zeta potential was 4, which indicates a partial neutralization effect between the positively charged NH groups and the oxygen-containing groups formed on the surface of boron nitride in contact with negatively charged water. In addition to electrostatic stability, the uniform dispersion of the nanoplates is due to the increased hydrophilicity due to the attachment of amine groups, the low thickness of the plates and uniform dispersion after ball milling.

Spatial stability Spatial stability is achieved by surrounding the particle with layers of materials that are spatially bulky, such as polymers or surfactants. Such large-sized modifying agents create a spatial barrier against particle aggregation. For example, to prepare multilayer nanosheets with a small number of layers from commercial BN powder, Lewis bases such as long-chain hydrophilic or hydrophobic amine molecules can be used to form complexes with electron-deficient boron atoms. By functionalizing the surface of the nanosheets and their sheeting in the solution phase, they are dispersed into monolayers or multilayers with a small number of layers up to 6 layers.[12]

Their uniformity and stability in the solvent increases, which is due to the creation of steric hindrance. Figure (1) (2) The results showed that the functionalization of the sheets and, as a result, the thickness in the outer parts will be greater than in the inner parts, which is probably due to the folding of the sheets from the edges and the covering of those parts with the reactive agent. Other Lewis bases used to laminate H-BN sheets include inorganic bases such as sodium and potassium hydroxide, phosphine compounds or amines of the first, second and third types, amino acids, proteins, thiols or a mixture of them Surfactants are also used to stabilize nanofluids. [13]

However, the ability to use the surfactant at high temperatures is a major concern because at that temperature the bond between the nanoparticles and the surfactant is destroyed. As a result, the nanofluid loses its stability and settles. Also, the addition of surfactant causes problems such as reducing the thermal conductivity of the nanofluid (24) because it forms foam upon heating, while heating and cooling are normal processes in heat exchange systems. In addition, the surfactant molecules attached to the surface of the nanoparticles increase the thermal resistance between the nanoparticles and the fluid,[14]which reduces the effective thermal conductivity. In a study, the copolymer surfactant PluronicF68, which consists of a hydrophobic polypropylene oxide (PPO) block in the middle and two hydrophilic polyethylene oxide (PEO) blocks on both sides, was also used to increase the stability of nanosheets in aqueous solution. The 25 PPO block is adsorbed to the BN- sheets through hydrophobic interactions, while the PEO block is located in the aqueous phase and provides effective steric hindrance, resulting in successful sheeting and stabilization (Fig. (2)). Compared to small molecule ionic surfactants such as sodium colloid, F68 is able to reduce the density of nanomaterials dispersed in the solvent, which is due to its high hydration percentage. Also, due to its non-ionic nature, F68 removes impurities from mobile ions. This is important for dielectric systems because mobile ions may cause charge trapping and damage the system.[15]

In another study, hydroxylated boron nitride nanosheets were prepared by heating BN- in air to introduce a large amount of oxygen into the boron nitride network, and then the boron nitride sheets were stirred in deionized water to prepare the desired product. The results showed that these sheets were able to form a stable suspension without the use of sonication (Figures) and (3)



Of course, the use of mild ultrasound waves would be required to increase the speed of spreading the sheets. The thickness obtained was 90, which, considering the monolayer thickness of boron nitride (33), was laminated to a thickness of 2 layers. The efficiency of the dispersed system was reported to be

6.3- Viscosity

Viscosity in nanofluids depends on the geometry and surface properties of the filler. According to studies, particle aggregation increases viscosity due to structural constraints on rotational and translational Brownian motions.[16]

A group of researchers investigated mineral oil containing 2D BN- and graphene nanostructures at low percentages (0.11). It was observed that the viscosity of the nanofluid decreases significantly with increasing temperature from 16 m/s at room temperature to 2.2 at 100°C, while the increase in viscosity with the addition of 2D fillers is very small (2) at 400°C. This is considered an advantage for systems with low filler contents because the increase in viscosity reduces the thermal conductivity and also the flow properties of the fluid. In addition, the small relative increase in viscosity (30) at 35°C fillers indicates the absence of particle aggregation in the fluid.

7.3- Brownian motion

Many researchers have found that Brownian motion, which is the random and irregular motion of particles, is a key mechanism for heat transfer in nanofluids. Brownian motion only exists when the particles are very small in the fluid; as the particle size increases, the effect of Brownian motion disappears. In a study, four possible micro-mechanisms for increasing the thermal conductivity of nanofluids were proposed, including collisions between fluid molecules, heat diffusion between nanoparticles suspended in the fluid, Brownian motion, and thermal interaction of moving nanoparticles with fluid molecules, among which Brownian motion was chosen as the main factor in thermal conductivity. 6 and 27 In the case of nanofluids based on BN particles, heat is transferred by two mechanisms. H-BN particles create heat diffusion channels through which electrons transfer heat. Brownian motion of particles is the second heat transfer mechanism in which particle motion leads to heat transfer. 22)[17]

3-8- The effect of temperature

The effective thermal conductivity of nanofluids and their Brownian motions increase with increasing temperature. A group of researchers investigated the temperature dependence of 25 to 50 BN-nanoplates dispersed in mineral oil fluid It was observed that the thermal conductivity of the nanofluid increases with increasing temperature and BN- concentration; while the thermal conductivity of the fluid without filler does not change with temperature change. The increase in thermal conductivity of h-BN-based nanofluid with increasing temperature is not only due to the diffusion phenomenon, but also Brownian motions have been effective in this increase. In such a way that an 80% increase in thermal conductivity was observed for the aforementioned nanofluid with a concentration of 0.1 at temperatures up to 50.[18]

- **Conclusion**

Nanofluids are a new generation of fluids with great potential in industrial applications. In nanofluids, due to the small size of the particles, a significant amount of impurity corrosion and pressure drop problems are reduced, and the stability of the fluids against sedimentation is significantly improved. To increase the stability of the nanofluid suspension in order to increase the thermal conductivity, surface active agents and physical or chemical bonding of polymer chains on the surface of nanostructures can be used. Other factors affecting the thermal conductivity of nanofluids include the amount of nanofiller, the viscosity of the nanofluid, and the temperature of the system used. The presence of nanofillers in nanofluids causes thermal conductivity to change with temperature, while without fillers, thermal conductivity is not dependent on temperature.

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