Mechanical Properties and Application of Graphite and Graphite-based Nanocomposite : A Review

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Abstract
With the recent advancement in nanotechnology, there has been significant progress in the research and development of carbon-based nanoparticles. Graphite, a naturally occurring allotrope of Carbon, exhibits completely different properties in its macromolecular scale than in its larger scale. This review article explores the fundamental properties of graphite nanoparticles (GNP) and its relevance and uses in the industry. The article takes both theory and experimental approach to establish a clear boundary between theoretical and experimental results. Graphite nanoparticles when mixed with a base fluid depending on its use and application, exhibit significant changes in the fluid properties even with the very low concentration. This distinctive phenomenon has applications ranging from direct solar energy absorption to enhancement of thermal conductivity in machineries. However, the use of GNP remains unexplored as further research and development is yet to be done. The article can be a good resource for scholars who want to gain a fundamental understanding of graphite nanoparticles and gain a foundation for the study of other nanoparticles.
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1. Introduction

1.1 History

Graphite is found naturally in metamorphic rocks on most continents including South America, Asia and North America. It is formed when carbon is subjected to intense heat and pressure. This causes production of sedimentary carbon compounds which often develop as flakes or crystalline layers within metamorphic minerals [1]. Naturally occurring graphite can be categorized into three main groups: flake graphite, crystalline vein graphite, and amorphous graphite. These three categories of graphite each hold differing physical properties depending on formation [2]. The properties of graphite have been extensively researched throughout the last century. Through those studies graphite has been found to possess the highest natural stiffness, resistance to chemical reactions, and impressive strength sustaining in temperatures exceeding 3600 ^{o}C [2], [3]. Graphite is an anisotropic element as can be seen by the fact that it also has excellent electric and thermal conductivity within the layers and has less thermal and electrical conductivity perpendicular to the layers. Due to the anisotropic properties, the layers of carbon can often slide past each other with little resistance, making it an ideal material for applications within lubrication [4]. Additionally, graphite has various other applications such as utilization in water purification, optical fiber technology, and fuel cells [5].

1.2 Aim of this review article

This review paper is primarily focused on discussing the synthesis and properties of graphite and graphite-based nanocomposites, especially as relating to its thermophysical properties such as thermal conductivity, viscosity, and specific heat. In the same vein, the article explores the various theoretical models and experimental studies that have been carried out in this area of research including modern advances in flow properties.

Understanding the structure and chemical composition of graphite, preparation and processing techniques for graphite-based nanocomposites and how graphite-based reinforcement enhances the mechanical properties of nanofluids are the central themes covered in this paper. Further, the paper reviews important research undertaken in the areas of physical phenomena of graphite-based nanocomposites such as stability, dynamic motion, properties and heat transport compared to other prominent nanocomposites.

The paper ends with a reinforcement of how nanofluids have been used in practical applications and use cases for graphite nanocomposites, including potential challenges in further research and industrial applications. The paper is intended to be a wealth of information for researchers looking to research and learn more about advances in graphite nanocomposite research as the paper covers extensively the numerous research areas of graphite nanocomposites and provides a solid basis for comparison to other nanocomposites

2. Preparation/Synthesis of Graphite nanofluids

Graphite contains a special type of atomic network called atomic layered network which is represented by a hexagonal atomic network composed by parallel planes of carbon atoms as shown below in fig.1.

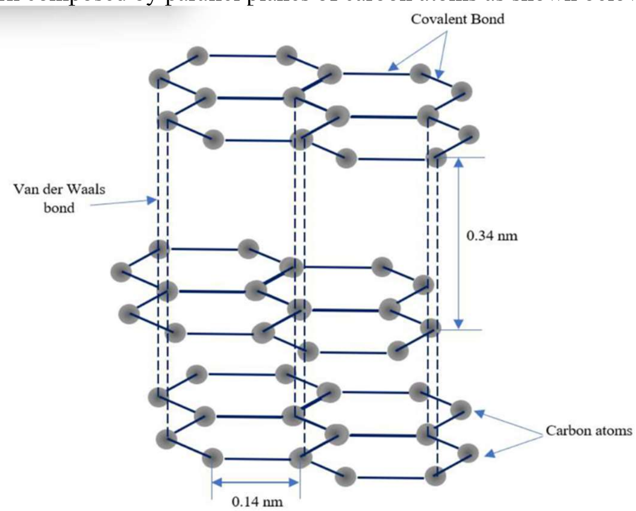

Figure 1. Graphite structure

2.1 Single-step Method

One of the most common methods used for the preparation of graphite nanofluids is a single step method. This method involves the synthesis of graphite nanofluids by exfoliating graphite flakes in a liquid medium [6]. Various liquid media, such as water, ethylene glycol, and oil, can be used as a base fluid. The exfoliation process is achieved by the application of sonication, which separates the graphite flakes into thin layers, the resulting product is a homogeneous nanofluid consisting of individual graphite layers dispersed in the liquid medium [7].

In a recent study, kang et al. [8], synthesized graphite oxide nanofluids using a single-step method. They used water as a base fluid and added a surfactant to improve the stability of the nanofluid. The exfoliation process was carried out using a high-power ultrasonic probe. The resulting nanofluid showed excellent thermal conductivity, which is essential for heat transfer applications. Another study conducted by Schedy et al. [9], synthesized yellow graphite nanofluids using a single-step method in organic solvents including ethylene glycol.

In conclusion, the single-step method is a simple, cost-effective, and efficient method for the preparation of graphite nanofluids. It involves the exfoliation of graphite flakes in a liquid medium using sonication. The resulting nanofluids show excellent thermal properties and can be used as heat transfer fluids in various engineering and industrial applications. Several studies have demonstrated the effectiveness of the single-step method in the synthesis of graphite nanofluids with different base fluids and surfactants. Chemical vapor deposition and Laser ablation has been widely used for graphite syntheses.

2.1.1 Chemical vapor deposition (CVD)

CVD is a method to form thin films by chemical reaction on the surface of substrates by using one or more gaseous compounds or elemental substances containing thin-film elements. CVD is a crucial material preparation method, which plays an essential role in precious metal thin films and coatings [10]–[12]. It contains variable processes like atmospheric-pressure chemical vapor deposition (APCVD) [13], low-pressure chemical vapor deposition (LPCVD) [14], plasma-enhanced chemical vapor deposition (PECVD) [15], or plasma-assisted chemical vapor deposition (PACVD) [16], and laser-enhanced chemical vapor deposition (LECVD) [17], [18].

Graphite formation by chemical vapor deposition is a very known technique to synthesize thin graphite films of nanometer thickness. Obraztsov et al. [19], found that well-ordered graphite films of nanometer thickness have been grown on Ni substrates by chemical vapor deposition from hydrogen–methane gas mixture activated by DC discharge. The ridges have been formed due to the difference in thermal expansion coefficients for graphite and nickel. The film thickness has been estimated as 1.5 ± 0.5 nm.

Graphite thin films could be formed at growth temperatures up to 900 ^oC [20]. By Chlorination of Fe3C at temperatures of 400 oC and above Dimovski et al. [21], found that amorphous carbon is formed at temperatures of 400– 500 ^oC, Flakes and ribbons of nanocrystalline graphite formed at 600–1100 ^oC, while graphite ordering increases with temperature, However the formation of microcrystalline graphite and millimeter-size graphite crystals occurs above the eutectic point in the Fe/Fe3C system.

To synthesis a hybrid graphite nanowires, CVD is an applicable method as Vlasov et al. [22], successfully produced Diamond-Graphite Nanowires with lengths up to a few hundred nanometers by Microwave Plasma

Chemical Vapor Deposition with nitrogen gas added. This hybrid material consists of a single crystalline diamond core of 5–6 nm in diameter oriented along the [110] principal axis and graphitic shells of different thickness covering the core.

CVD method also been used to deposit nanomaterials on graphite surfaces, as Holzapfel et al. [23], deposited nanosilicon on the surface of fine particle graphite (TIMREX KS6) to give a silicon⁄graphite "compound" material with 7.1 wt. % silicon, homogeneously distributed on the carbon surface as very small particles (10-20 nm).

2.1.2 Laser ablation

Graphite laser ablation is a process that involves the use of a laser beam to ablate, or remove, material from a graphite surface [24]. The quality and number of layers in the synthesized material could be controlled by tuning the laser parameters [25].

The efficiency of graphite laser ablation is significantly influenced by focus position, laser power, pulse duration, and ablation depth, they found that in laser machining with enough pulse energy, the ablation width was mainly determined by the laser propagation properties, and the ablation depth would achieve the maximum value at a defocusing position rather than the focal plane [26].

Another study found that, increasing the laser power and pulse duration led to an increase in the efficiency of the ablation process, while decreasing the spot size had the opposite effect, also the effect of the laser was much stronger for the dry ablation than the wet ablations [27]. However, the Absorption coefficient of graphite is measured to be higher by using a laser beam with a shorter wavelength [28].

2.2 Two-step method

The preparation of graphite nanofluids is usually performed by dispersing graphite nanoparticles in a base fluid. One of the most used methods for the preparation of graphite nanofluids is the two-step method, which involves the synthesis of graphite nanoparticles followed by their dispersion in a base fluid.

In the first step, the graphite nanoparticles are synthesized using various methods such as chemical vapor deposition [29], exfoliation [30], and ball milling [31]. Among these methods, ball milling is considered as an effective sustainable technique for the preparation of graphite nanoparticles, specifically graphite oxide. This method involves the mechanical milling of graphite flakes in the presence of a milling agent, which results in the formation of small-sized graphite particles. Panjiar et al. [32], demonstrated that mechanical milling can be an effective tool to synthesize stress free nanosized graphite particles in bulk.

In the second step, the synthesized graphite nanoparticles are dispersed in a base fluid using a surfactant or a dispersant. The choice of the base fluid depends on the intended application of the nanofluid. Water, ethylene glycol, and oils are some of the commonly used base fluids for the preparation of graphite nanofluids [33]. The dispersion of the graphite nanoparticles in the base fluid is usually achieved using ultrasonication or magnetic stirring. The dispersion process should be performed carefully to avoid the aggregation of the nanoparticles, which can affect the properties of the nanofluid.

The two-step method for the preparation of graphite nanofluids has been widely used due to its simplicity and effectiveness. The method allows the control of the size and concentration of the synthesized nanoparticles and the dispersion in the base fluid. The prepared nanofluids have shown improved thermal conductivity and are being explored for various applications such as in electronics cooling, solar thermal systems, and lubricants.

3. Thermophysical properties of Graphite based Nanofluids

3.1 Theoretical models

Graphite is a naturally occurring mineral that has several industrial applications, including as a lubricant and as an electrode material in batteries [34]. Graphite consists of layers of carbon atoms arranged in a hexagonal lattice structure, these layers can slide over each other, making graphite an excellent lubricant [35]. The properties of graphite can be modified by changing the size and thickness of the graphite layers [36].

Nanoparticle cluster is a common phenomenon observed in graphite, as graphite nanoplatelets tend to cluster together due to van der Waals forces between them [37]. This clustering can affect the properties of the graphite, such as its electrical conductivity and thermal stability. Some studies suggest that the dispersion of graphite nanoplatelets can be improved by adding a surfactant or by using sonication [38], [39].

The size of the graphite nanoparticles also has a significant impact on their properties. A study by Kumar et al. [40] found that the electrical conductivity of graphite nanoplatelets increases with decreasing particle size, this is due to the increased number of edges and defects in the smaller particles, which provide more sites for electron transport. The study suggests that smaller graphite nanoparticles could be used to improve the performance of electronic devices.

Finally, the effect of temperature on graphite properties is an important consideration. A study by Abdullah et al. [41], found that the coefficient of thermal expansion of graphite-based interatomic distance is negative and tends toward zero with increasing temperature. This is due to the anharmonic vibrations of the carbon atoms in the lattice structure. The study suggests that this thermal expansion could be a factor to consider in high-temperature applications of graphite.

Overall, the properties of graphite can be modified by controlling the size, thickness, and temperature of the material. These factors are important considerations for the use of graphite in various industrial applications.

3.2 Thermal conductivity measurement techniques

Graphite is a versatile material with unique properties that make it suitable for various applications. One of its outstanding characteristics is its high thermal conductivity, which makes it an ideal candidate for heat dissipation in electronics and energy storage systems. To measure the thermal conductivity of graphite based nanofluid, various techniques have been developed. One of the most widely used methods is the parallel plate steady-state (PPSS) method [42]. The PPSS method involves placing a sample of graphite based nanofluid between two parallel plates, each maintained at a constant temperature, and measuring the heat flow through the sample [43]. This method has been used to measure the thermal conductivity of graphite at room temperature, as well as at high temperatures up to 2400 K.

Another commonly used technique for measuring the thermal conductivity of graphite is the laser flash (LF) method. This method involves heating a small portion of the sample with a laser pulse and measuring the temperature rise as a function of time using a thermocouple. The thermal diffusivity and specific heat of the material are determined from the temperature rise data, and the thermal conductivity is calculated from these parameters [44]. The LF method has been used to measure the thermal conductivity of graphite composites at various temperatures, however the results showed this method is less accurate at a lower temperature (room temperature) [45].

The transient hot wire approach is another technique for measuring the thermal conductivity of graphite [46]. This method involves passing an electric current through a thin wire, which is in contact with the sample, and measuring the temperature rise of the wire as a function of time [47]. The thermal conductivity is calculated from the temperature rise data and the thermal diffusivity of the material. The transient hot wire approach has been used to measure the thermal conductivity of various types of graphite, including isotropic and anisotropic graphite [48]. The transient plane-source is another technique for measuring the thermal conductivity for extremely high thermal diffusivity materials, such as graphite [49].

In conclusion, there are several techniques for measuring the thermal conductivity of graphite, including the parallel plate steady-state (PPSS) method, laser flash (LF) method, transient hot wire approach, and transient plane-source method. These methods have been used to study the thermal conductivity of various types of graphite, at different temperatures and conditions, and can provide valuable information for various applications of graphite.

3.3 Specific heat

The specific heat of a material is the amount of heat energy required to raise the temperature of one gram of the material by one degree Celsius, and its related directly to the atomic structure [50]. One study by Tavman et al. [51], measured the heat capacity of graphite nanocomposites using differential scanning calorimetry (DSC) in the temperature range of 40-100 ºC. They found that the specific heat of graphite was higher than previously reported values and that it increased with temperature .

Another experimental technique for measuring the specific heat of graphite is pulse current heating. This involves applying a short pulse of heat to a small sample of the material and measuring the resulting temperature change. A study by Matsumoto and Ano [52], used this technique to measure the specific heat of ribbon-shaped graphite, in the temperature range of 1500-3000 K. They found that the specific heat increased with temperature increases.

Overall, the experimental results for the specific heat of graphite generally agree with theoretical predictions based on the Debye model, which describes estimating the phonon contribution to the specific heat (Heat capacity) in a solid [53]. However, some discrepancies have been observed at very low temperatures, which may be because of impurities or defects in the material. More recent studies have also explored the specific heat of graphene, a single layer of graphite, which exhibits unique electronic and thermal properties that differ from bulk graphite [54].

3.4 Density

The density of graphite-based nanofluids is an important thermophysical property that has been widely studied in recent years. The density of these nanofluids is significantly influenced by the concentration and size of the nanoparticles, as the concentration and size of the nanoparticles increase, the density of the nanofluid also increases . This is because the addition of nanoparticles to the base fluid increases the mass of the nanofluid, leading to an increase in density.

In addition to the concentration and size of the nanoparticles, the density of graphite-based nanofluids is also influenced by the type of base fluid used. Said et al. [55], found that the density of nanofluids prepared with water as the base fluid was significantly higher than those prepared with ethanol or ethylene glycol . This is likely due to the higher surface tension of aqueous fluids, which leads to a higher particle volume fraction and, in turn, a higher density.

The shape of the nanoparticles can also have an impact on the density of graphite-based nanofluids. Bashirnezhad et al. [56], conducted a study on the thermophysical properties of these nanofluids and found that the density of nanofluids prepared with spherical nanoparticles was higher than those prepared with irregularly shaped nanoparticles. This is likely due to the more efficient packing of the spherical nanoparticles, leading to a higher particle volume fraction and a higher density.

The temperature of the nanofluid can also influence its density. The density of graphite-based nanofluids decreases with increasing temperature, due to the expansion of the fluid and the decrease in the particle volume fraction [57]. This effect is more pronounced at higher nanoparticle concentrations, as the decrease in particle volume fraction has a greater impact on the overall density of the nanofluid.

3.5 Viscosity

In terms of viscosity, classical models have been used to predict the behavior of graphite-based materials. However, experimental techniques have been utilized to measure the viscosity of graphite-based materials more accurately. These techniques include capillary viscometer [58], concentric cylinders [59], and the cone and plate approach [60].

Several experimental studies have been conducted to understand the factors that affect the viscosity of graphite-based materials. For example, the effect of temperature has been investigated, with higher temperatures resulting in decreased viscosity [61], [62].

Other factors that have been studied include pH and sonication time. It has been found that higher pH levels can increase the viscosity of graphite-based materials [63], while longer sonication times can reduce in-plane dimension of graphite flakes [64], and decrease the viscosity accordingly.

Overall, the viscosity of graphite-based materials has been extensively studied through both classical models and experimental techniques. Various factors have been found to influence viscosity, including temperature, nanoparticle concentration, size and shape, pH, and sonication time.

4. Mechanical properties

4.1. Efficient electric conductivity

Graphite is a highly conductive material, making it an excellent choice for use in various electrical applications [65]. In fact, its electrical conductivity is so high that it is often used as the standard for measuring and improving the electrical conductivity of other materials [66]. This high level of conductivity is due to the unique structure of graphite, which is composed of layers of carbon atoms that are arranged in an open honeycomb network containing two atoms per unit cell in each layer [67].

One of the most significant advantages of using graphite in electrical applications is its ability to conduct electricity efficiently. This is because graphite has a high electron mobility [68], meaning that electrons can move freely through the material. As a result, graphite is often used in the construction of electrodes and other components of electrical circuits. According to a study by Chang Hu and Chu, "graphite electrodes have been found to be effective in many different types of electrochemical applications, due to their high electrical conductivity and low resistance" [69].

In addition to its high electrical conductivity, graphite is also a relatively inexpensive material [70]. This makes it an attractive option for use in electrical applications where cost is a primary consideration. Also, graphite has been shown to be a cost-effective material for use in various electrical applications, including batteries [71], fuel cells [72], and supercapacitors [73].

Overall, by using graphite instead of more expensive materials, manufacturers can produce high-quality electrical components at a lower cost. And as research continues in this area, it is likely that graphite will continue to be an important material for the development of new and innovative electrical technologies.

4.2. Excellent heat conductivity

Heat conductivity is a measure of a material's ability to conduct heat [74], which is important in various applications, such as in the production of electronic components and heat exchangers [75]. Graphite exhibits excellent thermal conductivity due to its unique crystal structure, which allows it to conduct heat in all directions [76]. This property makes graphite an ideal material for use in high-temperature applications where heat transfer is critical.

Moreover, the thermal conductivity of graphite is further enhanced by its high degree of anisotropy [77]. Graphite is composed of layers of carbon atoms arranged in a hexagonal lattice structure. The carbon atoms in each layer are strongly bonded to each other through covalent bonds, but the layers themselves are held together by weaker Van der Waals forces. This weak interlayer bonding allows heat to be conducted quickly and efficiently in the plane of the layers, while heat transfer between the layers is much slower [78]. As a result, graphite exhibits high thermal conductivity in the plane of the layers but low thermal conductivity perpendicular to the plane, which is known as its anisotropic thermal conductivity [79].

The exceptional thermal conductivity and the phase change of graphite makes it an attractive material for use in various industries. In the electronics industry, graphite is used as a heat spreader to dissipate heat generated by electronic components [80]. It is also used in heat exchangers and other thermal management applications where efficient heat transfer is required [81]. Bagheri et al. [82], reported that the graphite-based heat exchanger outperforms a similar heat exchanger made from aluminum, rejecting more than 20% more heat from the hot flow stream (water) to the cold flow streams (air).

In conclusion, graphite's high thermal conductivity makes it an ideal material for use in high-temperature applications, such as in the electronics industry and thermal management applications. With the increasing demand for high-performance electronic devices, the demand for graphite is expected to grow in the future [83].

4.3. Highest natural stiffness

The natural stiffness of graphite is considered one of the highest among all known materials, with a Young's modulus of up to 1.13 TPa [84]. The high stiffness of graphite can be attributed to its unique layered crystal structure, which enables it to withstand high loads without deforming [85]. This stiffness of graphite has significant implications in various fields such as aerospace, automotive, and construction, where materials with high stiffness are essential. For instance, graphite-based materials are utilized in the construction of bridges and buildings as a reinforced cementitious composites, where high stiffness is necessary to maintain structural integrity under heavy loads [86]–[88].

Despite its exceptional stiffness, graphite also exhibits anisotropy in its mechanical properties, with stiffness values varying depending on the orientation of the crystal structure and the testing temperature. This characteristic has been extensively studied by various researchers, including Pappis and Blum [89] ,in their paper, where they analyzed the temperature dependence of pyrolytic graphite, the findings of their study suggest that The ultimate strength of pyrolytic graphite in tension, bending, and compression has been found to increase considerably with increasing test temperature, also, graphite exhibits significantly higher stiffness in the direction perpendicular to the basal plane compared to parallel to it.

4.4. Can work in temperature exceeding 3400 ºC

It has been found that graphite can withstand temperatures exceeding 3400 oC without external insulation, shielding or even significant structural damage or degradation [90]. This exceptional performance is due to the unique arrangement of carbon atoms in the material, which creates strong covalent bonds and a high degree of thermal conductivity [91]. These properties make graphite a valuable material for high-temperature applications in industries such as aerospace, metallurgy, and nuclear engineering.

Recent studies have demonstrated the potential of graphite-based materials for use in extreme high-temperature environments. For example, researchers have developed high-density graphite composites that can operate at temperatures up to 3600 ºC [92], making them suitable for applications such as thermal protection systems for spacecraft and re-entry vehicles [93]. In addition, graphite has also been investigated for use in next-generation nuclear reactors, where it can provide excellent thermal conductivity and stability in high-temperature environments [94].

Graphite's ability to withstand extreme temperatures is also attributed to its high melting point, which is in the range of 4000 or 5000 K [95]. This property makes graphite an ideal candidate for use in high-temperature furnaces and other high-temperature processing equipment [96].

In conclusion, graphite's ability to withstand temperatures exceeding 3400 ºC without significant structural damage or degradation makes it an ideal candidate for use in high-temperature processing equipment, thermal protection systems for spacecraft, and next-generation nuclear reactors, among others. Graphite's potential for use in such applications underscores the importance of ongoing research into the material's properties and performance characteristics.

4.5. Effectively resistant to chemical reactions

Graphite is widely used in the chemical and petrochemical industries because of its exceptional chemical resistance [97]. Graphite's layers of carbon atoms can withstand high temperatures and pressures. As a result, graphite can be used in various applications, such as heat exchangers and reactor vessels, where it is exposed to harsh chemical environments [98], [99].

Moreover, graphite's chemical resistance is attributed to its high carbon content, which forms a protective layer on the surface of the material. This layer prevents the material from reacting with the surrounding chemicals and can withstand high temperatures and pressures [100]. In addition, graphite's non-porous structure also contributes to its chemical resistance [101], making it an ideal material for use in harsh chemical environments.

Finally, graphite's unique properties have been studied extensively, and researchers continue to explore its potential applications in various fields. For instance, graphite epoxy composites have been used in the shielding of high energy radiation, because of its ability to absorb radiation [102]. In conclusion, graphite's ability to resist chemical reactions effectively is due to its unique structure, high carbon content, and non-porous nature. This makes it an ideal material for use in various applications, particularly in harsh chemical environments.

4.6. Self-lubricating

One of the significant characteristics of graphite is its self-lubricating property. The self-lubricating feature of graphite is attributed to its layered crystal structure, which enables the sheets to slide over each other . As a result, graphite acts as a solid lubricant and reduces friction, wear, and heat generation in machinery components [103].

The self-lubricating property of graphite is utilized in the manufacturing of bearings, seals, and other machinery components [104]. Graphite-based materials are often used as a replacement for conventional lubricants, such as oil and grease, in high-temperature and high-load applications [105]. According to a study by Wang et al. (2017), graphite can significantly reduce friction and wear in metal-on-metal contact at temperatures ~1000 ^{o}C [106], making it an ideal solid lubricant for applications in harsh environments.

Furthermore, graphite's nanocomposites such as TiO2/graphite [107], composites have been used as self-lubricating materials due to the superior lubricating effect of graphite during sliding. Omrani et al. [108], study the influences of graphite reinforcement on the tribological properties of self-lubricating aluminum matrix composites for green tribology, sustainability, and energy efficiency, they concluded that by bringing self-lubricating composites into different operating systems is a solution to reduce the use of external toxic petroleum-based lubricants in sliding contacts in a way to help the environment and reduce energy dissipation in industrial components for strategies toward sustainability and energy efficiency.

In conclusion, the self-lubricating property of graphite is an essential characteristic that makes it a unique and valuable material for various industrial applications. Its ability to reduce friction, wear, and heat generation in machinery components, even at high temperatures, makes it an ideal solid lubricant.

5. Stability of Graphite nanofluids

5.1 Stability characterization/ measurement technique

One of the most used techniques for graphite stability characterization is X-ray diffraction (XRD). It is a non-destructive technique that uses X-rays to measure the diffraction patterns of a material's crystal structure, primarily at the atomic or molecular level [109]. The technique provides valuable information on the chemical composition, crystal structure, and lattice parameters of the material under investigation. Several studies have shown that XRD is an effective method for characterizing the stability of graphite [110]–[112]. For example, the XRD analysis of graphite can reveal the degree of graphitization, the presence of defects, and the orientation of the graphite flakes [113].

Another commonly used technique for graphite stability characterization is Raman spectroscopy. This method involves the use of a laser to measure the vibrational frequencies of the atoms structure [114]. The technique provides information on the structural and chemical properties of the material, including the degree of graphitization, the presence of impurities, and the extent of defects in the graphite structure[114], [115]Click or tap here to enter text.. Several studies have shown that Raman spectroscopy is a sensitive and reliable method for graphite stability characterization [116], [117]. Also, Canado et, al. [118], shows that Raman spectroscopy can be used as an alternative tool for measuring the degree of stacking order of graphitic systems.

Scanning electron microscopy (SEM) is another useful technique for graphite stability characterization. This method involves the use of a high-energy electron beam to create images of the material's surface [119]. The images can reveal information on the morphology, structure, and defects of the graphite material [120], [121]. SEM is particularly useful for studying the surface properties of graphite and graphite-based materials, including the degree of surface oxidation and the presence of surface contaminants [122].

In conclusion, graphite stability characterization is a crucial step in the production and application of graphite-based products. XRD, Raman spectroscopy, and SEM are three commonly used techniques for this purpose. These methods provide valuable information on the structural, chemical, and morphological properties of graphite, and can help to optimize the performance and durability of graphite-based products.

5.2 Instability effect on the properties of Graphite-nanofluid

The instability effect on the properties of the graphite-nanofluid is a significant challenge in its practical application. The instability can be due to particle aggregation, sedimentation, and agglomeration, which may affect the thermal conductivity, viscosity, and stability of the nanofluid. This instability effect on graphite-nanofluid can be mitigated by proper dispersion of nanoparticles in the fluid, which results in the uniform distribution of particles in the nanofluid, as Mosleh et, al. [123] suggested, by gelling the nanofluid in the room temperature. Also, Ali et al. [124], considered the gyrotactic microorganisms to maintain and improve nanoparticle stability and avoid possible sedimentation.

Thermal conductivity and viscosity are critical parameters for efficient heat transfer in graphite-nanofluid.

The instability effect on thermal conductivity and viscosity is significant as it affects the uniform distribution of the nanoparticles in the fluid, thus hindering heat transfer and viscosity. According to Ali et al. [124], the aggregation of nanoparticles causes a reduction in thermal conductivity. Similarly, sedimentation of the particles causes the formation of non-uniform layers in the nanofluid, leading to a reduction in thermal conductivity [125].

Viscosity is another significant property of graphite-nanofluid that affects its stability. The instability effect on viscosity is due to the formation of clusters and agglomerates that increase the viscosity of the fluid [126]. Hence, it is essential to understand the instability effect on the graphite-nanofluid and implement suitable measures to improve its stability and enhance both the heat transfer and the viscosity.

6. Nanoparticles motion in a liquid

6.1 Interparticle forces.

In graphite, the two-dimensional planes of carbon atoms are stacked to form a three-dimensional solid; only London dispersion forces hold the layers together. As a result, graphite exhibits properties typical of both covalent and molecular solids [127]. Graphite has a high melting point of (more than 3,600°C), and this is because a lot of strong covalent bonds must be broken [128]. Also, the forces between the layers in graphite are weak, this means that the layers can slide over each other. This makes graphite slippery, so it is useful as a lubricant [129].

6.2 Forces between the nanoparticle and the base fluid

The forces between graphite nanoparticles and the base fluid play a significant role in determining the properties and behavior of graphite-based nanofluids. Each carbon atom in graphite is bonded to three other carbon atoms, these carbon atoms are linked by covalent bonds - which are very strong [130], [131]. Graphite is composed of stacked layers of graphene sheets, which are held together by the weak Van der Waals forces, including attraction and repulsions between atoms, molecules, and surfaces, as well as other intermolecular forces [132].

The strength and type of forces between the graphite nanoparticles and the base fluid can be influenced by various factors, such as the size and shape of the nanoparticles, the type of base fluid, and the concentration of the nanoparticles. However, van der Waals forces between the nanoparticles and the base fluid are typically the strongest and dominant at low concentrations, graphite layers can slide relative to each other, which is why graphite is a soft solid that we can easily transfer to paper through a gentle push [133].

The forces between the graphite nanoparticles and the base fluid can also affect the stability and aggregation of the nanofluid. The stability of the nanofluid is influenced by the balance of attractive and repulsive forces between the nanoparticles and the base fluid. At high concentrations, the repulsive forces between the nanoparticles can lead to aggregation and destabilization of the nanofluid, higher the repulsive forces between the nanoparticles—higher the stability of the nanofluid [134], [135].

7. Hybrid graphite nanofluids

7.1 Hybrid nanofluids theory

Hybrid nanofluids are a type of nanofluid that consists of a base fluid mixed with nanoparticles [136]. Hybrid graphite nanofluids have several unique properties that make them attractive for use in various applications, including lubrication[137], heat transfer and thermal management [138].

The behavior of hybrid graphite nanofluids can be described by several theories, including the percolation theory, the Brownian motion theory, and the thermophoresis theory. These theories help to explain the behavior of the graphite nanoparticles in the base fluid, and how they interact with each other and with the surrounding environment.

The percolation theory is a widely used model to explain the electrically conducting behavior of composites consisting of conducting fillers and insulating matrices [139]. According to this theory, the properties of the nanofluid are significantly influenced by the concentration of the graphite nanoparticles, and the behavior of the nanofluid changes dramatically as the concentration of the nanoparticles increases [140].

The Brownian motion theory is another important model for predicting the behavior of hybrid nanofluids [141]. According to this theory, the motion of the graphite nanoparticles in the base fluid is governed by their size, shape, and surface properties, as well as the properties of the base fluid, brownian motion and induced micro convection and mixing possibly significantly enhance the macroscopic heat transfer in nanofluid fuels [142]

The thermophoresis theory is a third important model for predicting the behavior of hybrid graphite nanofluids. According to this theory, the motion of the graphite nanoparticles in the base fluid is influenced by the temperature gradient in the system, with the nanoparticles tending to move towards regions of higher or lower temperature depending on their size and surface properties [143]

7.2 Hybrid graphite/nanofiller nanocomposites

Hybrid graphite nanofluids are a type of nanofluid that is composed of a mixture of different types of nanoparticles suspended in a base fluid. According to Cermak et al. [144], hybrid graphite nanofluids have gained significant attention due to their unique thermophysical properties, which can be tailored by adjusting the composition and concentration of the nanoparticles.

One of the key theories behind the behavior of hybrid graphite nanofluids is the principle of effective medium theory (EMT). It is a popular model for estimating the overall thermal conductivity of nanofluids based on their composition [145]. Petersen et al. [146], investigated the limitations of effective medium theory in multilayer graphite/hBN heterostructures, they showed that modes that are evanescent in air are extremely sensitive to the electronic details of the sheets near the structure boundary and that EMT poorly estimates the reflection of these modes, causing an overestimation of the Purcell factor. However, they offered an improved EMT, which gives far better convergence in the low-energy regime.

Another important theory in the study of hybrid graphite nanofluids is the principle of percolation theory (PT) [147]. According to Mirmohammadi et al. [148], PT is a mathematical model that is used to predict the behavior of nanofluids when the concentration of the nanoparticles reaches a critical threshold. Graphite suspensions show distinct behavior in the thermal conductivity at the electrical percolation threshold, including a sharp kink at the percolation threshold, below which thermal conductivity increases rapidly while above which the rate of increase is smaller, contrary to the electrical percolation behavior [149].

In addition to EMT and PT, there are several other theories that have been proposed to explain the behavior of hybrid graphite nanofluids. For example, Anwar et al. [150] proposed the use of a fractal model to predict the thermal conductivity of hybrid graphite nanofluids, while Bhattacharya et al. [151] proposed the use of a hybrid model based on both EMT and PT to predict the electrical conductivity of these materials.

Overall, the study of hybrid graphite nanofluids is an active area of research, with several different theories being proposed to explain their behavior. While much progress has been made in understanding these materials, further research is needed to fully understand their properties and potential applications.

7.3 Graphite/fiber hybrid composites

Graphite/fiber hybrid composites are materials that are composed of a combination of graphite and fiber reinforcement. These materials are known for their high strength, stiffness, and thermal stability, making them attractive for use in a variety of structural and high-temperature applications.

Carbon (graphite) fibers are very stiff, strong and light filaments used in polymer (usually epoxy) matrix composites for aircraft structures and jet engine parts [152], and it has a higher specific modulus than glass; it is also more resistant to elevated temperature and chemical exposure, but it is considerably more costly [153]. Generally, the strength and stiffness of fibers is significantly influenced by the type and orientation of the fiber around its axis [154]. For example, using fibers with a high aspect ratio, such as carbon fibers, can significantly increase the strength and stiffness of the composite material.

In addition to their mechanical properties, Carbon or graphite fibers exhibit excellent intrinsic thermal stability. Their mechanical properties (both specific axial Young's modulus and strength) are retained up to extremely high temperatures, making them suitable for use in high-temperature environments [155].

One of the key advantages of graphite/fiber hybrid composites is their ability to tailor the mechanical and thermal properties of the material through the selection of different fiber types and orientations [156]. For example, using fibers with a higher tensile strength can increase the overall strength of the composite, while using fibers with a high thermal conductivity can improve the thermal stability of the material.

Despite their many benefits, graphite/fiber hybrid composites are not without their challenges. One issue that has been identified is because of their chemical reactivity, the problem of their stability becomes critical in the presence of oxygen, either in the atmosphere at temperatures above ∼500 °C or in the composite (interface layer and matrix) [155] .In addition, carbon fiber is an abrasive material and increases the rate of wear on the tools used to cut it. This is exacerbated by the temperature sensitivities associated with carbon fiber machining – the material has low thermal conductivity, and very little heat is carried away in chips [157].

8. Molecular dynamic (MD) simulation

Molecular dynamic (MD) simulation is a computational technique used to study the behavior of molecules and materials at the atomic scale. MD simulation is often used to study the properties of graphite, as it allows researchers to understand the behavior of individual atoms and the interactions between them.

MD simulation can be used to understand the mechanisms responsible for the excellent thermal conductivity of graphite, which is due to the efficient transfer of phonons through the crystal lattice. Also, MD simulation can be used to study the mechanical properties of graphite, including its strength, stiffness, and fracture behavior, by applying axial tensile stress and in-plane shear stress on the simulation box through the modified NPT ensemble [158]. MD simulation can also be used to study the thermal properties of graphite, such as its heat capacity and thermal conductivity. According to Trevethan et al. [159], molecular dynamics simulations of single crystal graphite have been performed, incorporating point and extended defect structures formed as a result of thermally annealed radiation damage, their results provided a direct insight into how the underlying atomic scale defects and dislocations created by radiation damage can lead to material property changes, and demonstrate how this computationally efficient simulation method can be employed to reproduce crystallite changes in large-scale models of polygranular graphite.

One of the advantages of using MD simulation to study the properties of graphite is that it allows researchers to study the behavior of individual atoms and the interactions between them in detail, and it can provide valuable insights into the mechanisms responsible for the unique properties of graphite, which are not possible to obtain through experimental techniques alone. According to Alkhateb et al. [160], MD simulations prove that exfoliation improves mechanical properties of graphite nanoplatelet vinylester nanocomposites, it also revealed that there is minimal effect of bromination on mechanical properties of pure vinylester, bromination tends to enhance interfacial shear strength between graphite–brominated vinylester/graphene-brominated vinylester in a considerable magnitude.

In addition to its use in studying the graphite's mechanical and thermal properties, MD simulation can also be used to study the graphite's phase transformation. Boulfelfel et al. [161], used MD simulation to investigate the kinetic pathways of the pressure-induced transformation of graphite to various superhard candidate structures.

9. Brief overview of Graphite nanofluids, potential applications and the challenges

9.1 Automobile applications

Graphite is a material that has a variety of applications in the automotive industry. It is commonly used in the production of brake linings, gaskets and clutch materials, graphite also has a myriad of other industrial uses in lubricants, carbon brushes for electric motors, fire retardants, and insulation and reinforcements products [162].

According to HPMS Graphite [163], graphite Foil is an excellent graphite gasket sheet material, used in the automotive, petroleum and chemical, paper, and nuclear industries, it acts as a thermal barrier at high temperatures to provide outstanding reflectivity, and it and excellent seals for sealing high temperature valves, shafts, and flanges. Also, graphite foil is an excellent linings and protective layer for vessels containing hot or corrosive fluids.

In addition to its use in brake and friction materials, graphite is also used in the production of the solid lubricants, and One commonly used is electrographite as a replacement to the sheet metal cage of the bearing [164], the cage of graphite is during operation releasing graphite to the raceways and rolling element.

Another application of graphite in the automotive industry is in the production of fuel cells. Graphite used as a conductive material for the bipolar plates, which are an essential component of the fuel cell structure. Fuel cell graphite used to form bipolar plates must be pure and of high quality to improve electrical and thermal conductivity, as well as ensure long life operation [165].

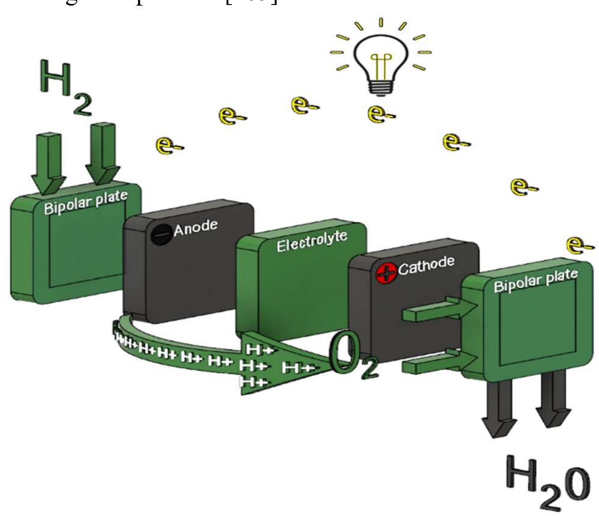

Fig. 2. Fuel Cell [165]

Additionally, the anode in Li ion batteries (LiBs) is made from graphite. A graphite anode is one of the things that make it a LiB and there are no substitutes. LiBs are smaller, lighter and more powerful than traditional batteries and have a flat voltage profile meaning they provide almost full power until discharged [166]. This makes it an important component in the production of electric vehicles, which are becoming increasingly popular as a more environmentally friendly transportation option.

Overall, the use of graphite in the automotive industry is widespread due to its unique properties and versatility. It is an important material in the production of a variety of automotive parts and systems, and its use is likely to continue to expand in the coming years.

9.2 Solar applications

9.2.1 Solar thermal collectors

Graphite solar thermal collectors are a type of solar energy technology that utilizes graphite as the primary absorber material. These collectors are designed to absorb solar radiation and convert it into thermal energy, which can then be used for a variety of applications, including water heating, space heating, and electricity generation.

Graphite solar nanofluids are a type of concentrated solar energy system that utilizes nanoparticles suspended in a fluid to capture and store solar energy. These systems are designed to be highly efficient, with the ability to capture and store solar energy at a much higher rate than traditional solar panels.

Graphite has several advantages as an absorber material for solar thermal collectors, It has a high thermal conductivity, which enables it to efficiently transfer heat from the absorber to the working fluid. According to Ladjevardi et al. [167], using graphite nanofluids having volume fraction around 0.000025%, it will be possible to absorb more than 50% of incident irradiation energy by just about 0.0045 $/L increase in cost, while pure water solar collector can only absorb around 27% of incident irradiation energy.

In addition to its high thermal conductivity and absorptivity, graphite is a good electrical conductor due to its the atomic structure, each carbon atom is bonded into its layer with three strong covalent bonds; this leaves each atom with a spare electron, which together form a delocalized sea of electrons loosely bonding the layers together [168]. That makes it well-suited for use in hybrid solar thermal systems that generate electricity. It is also resistant to corrosion against most common acids, making it a durable and long-lasting material for use in solar collectors. Graphite has the advantage of being low-cost material, and studies have reported that using graphite as the catalyst material helps in enhancing the electronic conduction and energy conversion efficiency of Dye-Sensitized Solar Cells [169].

In conclusion, the high thermal and electrical conductivity, high absorptivity and corrosion resistance of graphite in the solar thermal collectors has the potential to significantly improve the performance, stability and efficiency of these systems. However, further research is needed to fully understand the potential of these materials and to address any challenges that may arise.

9.2.2 Hybrid nanofluid in solar and photovoltaic/thermal (PV/T) systems

Photovoltaic Thermal (PV/T) combines the solar thermal and photovoltaic systems. This technique benefits from both light and heat of the solar radiation to produce electricity and hot fluids [170]. Using hybrid nanofluid in solar energy and photovoltaic/thermal (PV/T) systems can enhance the efficiency up to 60%, due to the increased value of Nusselt number in case of hybrid nanofluids as compared to the pure fluids. However, concentration and type of hybrid nanofluid are influential parameters for these enhancements [171].

Liang et al. [172], proposed a model in which the graphite layer is used underneath the water channel as shown in Fig. 3 and compared the performance with the conventional PV. The average electrical efficiency reported for the proposed PV/T model and conventional PV module was 6.46% and 5.15%, respectively. The highest electrical efficiency of a PVT collector filled with graphite can reach 7.2%. The highest Primary Energy Saving efficiency of PVT collectors filled with graphite was 48%.

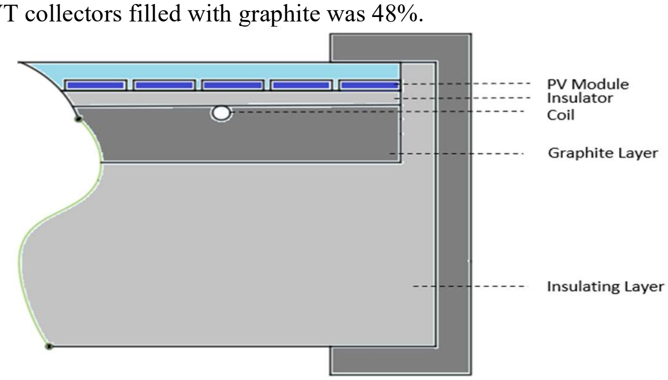

Figure 3. Layer diagram of PV/T collector uses a graphite layer [172]

According to Don et al. [173], Graphite/Carbon Black Counter Electrode can be considered excellent alternatives to the costly noble metals often employed in perovskite solar cells (PSCs) when deposited using a suitable technique, this method resulted in up to 8.81% power conversion efficiency and the devices prepared using this method exhibited the best stability in the air, retaining 71.1% of their original efficiency after 1600 h of continuous testing.

Despite the many potential benefits of using graphite-based nanofluids in Photovoltaic Thermal (PV/T), there are also some challenges that need to be addressed. One issue is the potential for the nanoparticles to settle out over time, leading to a decrease in the performance of the system. This can be mitigated by using a suitable carrier fluid and appropriate surfactants to maintain the stability of the nanofluid. However, Mosleh et al. introduced a solution for a nanoparticles settlement using alcohol based medium [123].

9.3 Mechanical applications

Graphite has several unique mechanical properties that make it an attractive material for a wide range of applications. These properties include high strength, high stiffness, and low density, which make it well-suited for use in structural and mechanical components [174].

One common application of graphite is in the production of bearings and seals. Graphite has excellent wear resistance and low friction properties, also carbon graphite is known to have self-lubricating properties [175], which make it well-suited for use in these types of components. Also, some turbine & compressor rings are manufactured from superior carbon graphite grades, including carbon graphite, electrographite and resin-bonded graphite for a variety of applications [176].

Another application of graphite is in the production of electrical contacts and connectors [177]. Due to the excellent electrical conductivity and low electrical resistance [178], graphite is considered an ideal candidate for use in these types of components.

Graphite coating with optimal thickness uniformity on gear exhibited a significant noise reduction, especially on axial vibration more than that of radial vibrations [179]. In addition to these applications, graphite is also used in the production of a variety of other mechanical components, including clutches, and valve seals [180]. In conclusion, the unique combination of strength, stiffness, and low density make graphite an attractive material for use in mechanical applications.

9.4 Reactor-heat exchanger

Graphite reactors and heat exchangers are commonly used in a variety of chemical and industrial processes due to their high strength, thermal stability, and corrosion resistance [181]–[183]. One of the key advantages of using graphite in reactor and heat exchanger applications is its ability to withstand high temperatures, as it can operate at temperatures up to 3,000°C [184], making it well-suited for use in high-temperature chemical reactions.

In addition to its high temperature resistance, graphite is also highly resistant to chemical corrosion[185]–[187]. Graphite is resistant to a wide range of chemicals, including acids, bases, and organic solvents [188], making it an ideal material for use in reactor and heat exchanger applications.

Despite its many advantages, there are some limitations to the use of graphite in reactor and heat exchanger applications. One issue is the potential for graphite to become brittle and crack under certain conditions [189]. To mitigate this issue, it is important to carefully design and operate the reactor or heat exchanger to avoid excessive stresses on the graphite.

9.5 Heat pipes and Electronics cooling

Graphite is a commonly used material in the construction of heat pipes [190], due to its high thermal conductivity and low thermal expansion (CTE), making it less prone to thermal expansion and contraction during temperature changes. Heat pipes are devices that are used to transfer heat from one location to another, and they are typically used in a variety of applications, including electronic cooling, space propulsion, and solar energy systems [191].

Despite their many advantages, graphite heat pipes do have some limitations. One issue that has been identified is the potential for graphite to oxidize at high temperatures (Over 600 °C) [192]. This can lead to a reduction in the thermal conductivity of the graphite, which can decrease the overall performance of the heat pipe. To mitigate this issue, it is important to carefully control the operating temperature of the heat pipe. Also, heat dissipation of graphite is limited by the poor thermal radiation in serving as a heat sink. However, Fan et al. [193], proposed composite foil with a sandwich structure of graphite-silver-polyimide, to prevent the object surface from overheating under direct sunlight, augmenting the dissipated heat generated by heat source, reducing the local high temperature of surface. Another challenge that has been identified with low yield and complex processes [194].

Despite these challenges, graphite is particularly well-suited for use in electronic cooling applications [195]–[197], where they can effectively transfer heat away from sensitive components.

9.6 Biomedical applications

Graphite has several potential biomedical applications due to its unique properties, including its unique thermal expansion combination, high strength, and machinability to meet the stringent requirements set for critical materials in the biomedical application, in addition to its high surface area. Graphite-based nanomaterials has been explored as a material for use in drug delivery systems [198], [199], biosensors [200], [201], and tissue engineering [202]–[204].

One area where graphite has been extensively studied is in the development of drug delivery systems. According to Aranda [205], graphite has been shown to have a high capacity for drug uptake and release, making it a potential alternative to traditional drug delivery systems. In addition to its potential use in drug delivery, graphite has also been explored as a material for use in biosensors. According to Clemmer et al. (2015), graphite has been shown to have a high sensitivity to various biological molecules, making it well-suited for use in the scanning Tunneling Microscopy studies. Entegris inc. [206], have developed biomedical grade graphite materials to be safely used in a variety of implantable applications, such as ultrasonic applications, the proven performance of this fine grain graphite allows it to be used in next-generation probes.

Another area where graphite has been explored is in tissue engineering. Lamprecht et al. [207], have explored the feasibility and potential of Aero-graphite as a scaffold for 3D cell growth, employing cyclic RGD (cRGD) peptides coupled to poly(ethylene glycol) (PEG) conjugated phospholipids for surface functionalization to promote specific adhesion of fibroblast cells, it has been shown a successful growth and invasion of the bulk material. Which proved that graphite-materials have a high biocompatibility and can be used as a scaffold material for tissue growth.

Despite its potential biomedical applications, there are also challenges associated with the use of graphite in the field. One issue that has been identified is the potential for graphite to cause cytotoxicity, or cell death. According to Zakrzewska et al. [208], graphite nanoparticles exhibited a negative impact on glioblastoma, but not on hepatoma cells, and they showed that the influence of the graphite nanoparticles on the stable, fluorescently labeled tumor cell lines and concluded that the labeled cells are suitable for drug cytotoxicity tests.

9.7 Space and Defense

Graphite has several properties that make it attractive for use in space and defense applications. Graphite has a high strength-to-weight ratio [209], and the special type of a hexagonal atomic network [210], makes it an ideal for use in structural components and materials for spacecraft and other aerospace applications.

Graphite plates are preferred as fixtures because they are inert and do not transfer any chemistry or metals to the aerospace metal being treated, except for the eutectic reaction [211], in addition to that, graphite is used for jet and rocket engine nozzles and Carbon/Graphite vanes, impellers and rotors move aviation fuel safely without the dangers of creating sparks to ignite fuel. Pyrolytic graphite has a long history of successful operation as a material of choice for solid propellant rocket exhaust nozzles, throat inserts, and guide vanes[212].

In addition to its use in aerospace and defense applications, graphite has also been used in the development of new materials and technologies for these industries. Researchers have used graphite to create new composite materials with improved mechanical and thermal properties for use in space and defense applications [213], [214]. Graphite has been used in several military applications, such as making a Graphite bomb [215], (also known as the soft bomb) is a non-lethal weapon which is used for shutting down the power supply systems of the enemy.

9.8 Desalination

Graphite has a high specific surface area, high electrical conductivity, and excellent corrosion resistance, making it an attractive material for use in desalination systems. One of the keyways in which graphite is used in desalination is as a membrane material. According to Golovakhin et al. [216], graphite has been analyzed as promising materials for water purification membranes, these membranes shown to be effective at removing salt from water, with high salt rejection rates and low fouling tendencies.

In addition to its use as a membrane material, graphite has also been explored for its potential use in desalination through the process of capacitive deionization. CDI involves the use of an electrical current to remove ions from water, and graphite has been found to be an effective material for use in CDI systems due to its high electrical conductivity and large surface area [217].

Despite its many potential advantages, there are also challenges associated with the use of graphite in desalination. One issue that has been identified is the high cost of graphite, which can make it less cost-effective than other materials. However, some researchers produced Graphite Coated Sand Grain Filters as a solution, and it could become a low-cost and simple way to purify water [218]. Additionally, the production of graphite membranes and other components requires a high level of precision, which can also increase the overall cost of the system. However, further research is needed to fully understand the potential of this material and to address the challenges associated with its use.

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