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Review

Mass Transport and Energy Conversion of Magnetic Nanofluids from Nanoparticles' Movement and Liquid Manipulation

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Abstract: Magnetic nanofluids, also referred to as ferromagnetic particle levitation systems, are materials with highly responsive magnetic properties. Due to their magnetic responsiveness, excellent controllability, favorable thermal characteristics, and versatility, magnetic nanofluids have sparked considerable interest in both industrial manufacturing and scientific research. Magnetic nanofluids have been used and developed in diverse areas such as materials science, physics, chemistry and engineering due to their remarkable characteristics such as rapid magnetic reaction, elastic flow capacities, and tunable thermal and optical properties. This paper provides a full and in-depth introduction to the diverse uses of ferrofluids including material fabrication, fluid droplet manipulation, and biomedicine for the power and machinery sectors. As a result, magnetic nanofluids have shown promising applications and have provided innovative ideas for multidisciplinary research in biology, chemistry, physics and materials science. This paper also presents an overview of the device construction and the latest developments in magnetic-nanofluid-related equipment, as well as possible challenging issues and promising future scenarios.

Keywords: magnetic nanofluids; mass transport; energy conversion

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1. Introduction

With the constant development of science and technological innovations, it has now become feasible to fabricate nanoparticles from diverse materials. A suitably great surface-to-volume proportion is one of the distinguishing features of nanoscale materials, which makes them uniquely superior in terms of capabilities. In the past few years, nanofluids have emerged as an attractive new type of thermal conductivity fluid because of nanotechnology. They have undergone tremendous growth and advancement. Relevant researchers and engineers are attempting to study and identify the regularities of the thermophysical features of such liquids, for which they propose new kinds of regimes and offer unconventional models to depict such actions and mechanisms. Nanofluids are nanoparticles (at the very least one size below 100 nm) that are suspended in a fundamental liquid, such as water, alcohol, oil, coolant, etc. [1].

During the last three decades, nanofluids have attracted a lot of attention in the fields of nanotechnology, thermal engineering, and other domains of application. Significant prospects for various sectors, including environment, energy, economy, and performance enhancement, are presented by scientific advancements and innovations in the domain of nanofluids [2]. It has been shown that the application of nanofluid technology materials can enhance both thermal conduction and conductive thermal transmission coefficients compared to fundamental liquids. With better thermal properties than water in thermal exchangers, nanofluids can be applied in a wide range of chilling and heating procedures. Therefore, by means of enhanced thermal transmission, it is possible to minimize or even avoid water consumption and waste in several circumstances. This provides a possible approach to solving the water consumption and manufacturing issues of large-scale industrial wastes such as those found in the petroleum and petrochemical industries. Moreover, strengthening the thermal properties of thermal exchangers can be achieved through their deformation. Ultimately, by enhancing thermal transfer, the dimensions of the thermal exchangers applied in such industries may be downsized. In addition, with the downsizing of the thermal exchanger, decreasing the stress of the pump by decreasing the length of the thermal transmission pipes is possible, which eventually reduces the dimensions of the entire equipment.

Stimulus-responsive materials have proven their usefulness in a broad field of applications ranging from scientific studies to real-world uses. Magnetic nanofluids, as one of the broadly researched functional materials, can show good reactions to outside magnetic fields. In a broadly defined sense, magnetic nanofluids are colloidal suspensions of ferromagnetic nanoparticles that can exhibit the characteristics of both fluids and magnetism. When subjected to an external magnetic field, magnetic nanofluids can respond by aligning their magnetic moment with the applied magnetic field, resulting in macroscopic magnetization. Because of this property, magnetic nanofluids can be used in the domains of microflow control and magnetic drug targeting. Ferromagnetic nanoparticles can be composed of magnetite (Fe_2O_3, γ-Fe_2O_3), magnetite (FeO-Fe_2O_3), or iron oxides accompanied by Ni, Co, Mg, Zn, etc. [3]. The grain diameter of a magnetite-based nanofluid is smaller than 10 nm. They are commonly coated or functionalized with extra molecules in order to prevent agglomeration and enhance functions. The ability of magnetic nanofluids to combine ultra-paramagnetic properties with regular liquid behavior is their most remarkable feature. This allows them to have magnetically controlled, elastic, and reversible flow, heat, light, and other physical characteristics, in addition to having a rapid and powerful magnetic reaction to relatively weakened magnetic fields [4]. These characteristics, along with the compatibility features between magnetic nanofluids and other materials, cause magnetic nanofluids to be one of the promising alternatives for many applications. The inception of magnetic nanofluids' design and usage can be traced back to the 1960s (at NASA), when colloidal suspensions of magnetic particles were developed and applied to manipulate spatial fluids by Stephen Pappell [5]. Since then, the physical and chemical features and manufacturing processes of magnetic nanofluids have been studied further and gradually refined. Significant progress in the theory and technology of magnetic nanofluids has led to a host of groundbreaking discoveries as well as a broadening of the applications of magnetic nanofluids. Besides their widespread use of power and the mechanical fields, scientists linked magnetic nanofluids with innovative optical or polymerizable materials, leading to a variety of combination development of composites, including polymer-like constructions, magnetic-responsive photonic crystals, and tiny robots [5,6]. Furthermore, when ferromagnetic fluids are incorporated into microfluidic systems, a large range of functional applications can be realized, from the operation of liquid droplets to on-demand compositing and testing [6]. As a result, they are regarded as one of the most promising flows in diverse areas of engineering, such as bio-engineering, heat generation, electronics, and power collection, among others.

In total, magnetic nanofluids provide a great deal of convenience to liquid and droplet handling and may be implemented in a multitude of domains such as bio-sensing, chemistry combination, and medical treatment [7]. Some applications of magnetic nanofluids are shown in Figure 1. With the magnetic force, magnetic sequential fluid microfluidics usually handle sequential flows or droplets produced sequentially in the microfluidic path. It is easy to control the fluids' velocity as well as the droplets' dimensions and properties, but controlling dissociated droplets is more challenging. For instance, magnetic nanofluids suffer from magnetic adhesion and magnetic drag effects that influence droplet formations of magnetic nanofluids and are dependent on the relevant flow velocity as well as on outer magnetic field strength [8]. Magnetic nanofluids could potentially boost the formation of polymer droplets, adjust their form, and depend on the magnetic flotation and dipole–dipole interactions generated by the magnetic field, thereby gathering the droplets into a length of chains, as designed in [9]. Magneto-digital microfluidics, in contrast to magnetic sequential stream microfluidics, are designed to deal with dispersed droplets in an independent manner. Besides managing the orientation, velocity, and style of liquid droplet motion, magneto-digital microfluidics possess the functionality to instruct liquid droplet transportation, blending, isolation, and distribution to work as a biological or chemical reactor [7,8]. In magneto-digital microfluidic applications, magnetic nanofluid characteristics can be broadly classified into three categories [9]. The first one is a magnetic cargo vessel: magnetic nanofluid droplets can be combined into stationary ones, loading or emitting the goods, and segregated from the droplets. The second is the loaded iron magnetic particles: droplets are loaded with iron magnetic particles, which can exhibit a fast reaction to magnetic stimulation. The third is the magnetic fluid marbles: iron magnetic particles cover the surface of liquid droplets to produce steady fluid marbles, which induce the marbles to travel and cause partial opening to disclose the droplets inside. Among the earliest uses of magnetic nanofluids were applications in the fields of mechanical and power projects. Their fluidity, temperature features, and thermo-magnetic counter-flow make the magnetic nanofluids serve a key function in the area of power generation such as in coolants, vibrating power harvesters, the use of heat exchangers, etc. In addition, researchers related to the domain of physics and work in engineering make use of the refractive stabilization features of magnetic nanofluids as components of sensitive machinery transducers, such as ambient force and magnetic energy sensors [6]. In addition, magnetic nanofluids have a far-reaching effect on the development of projects such as the building of optical equipment, the splitting of oil and water, the cleaning of water, and fluid conveyance pumping systems.

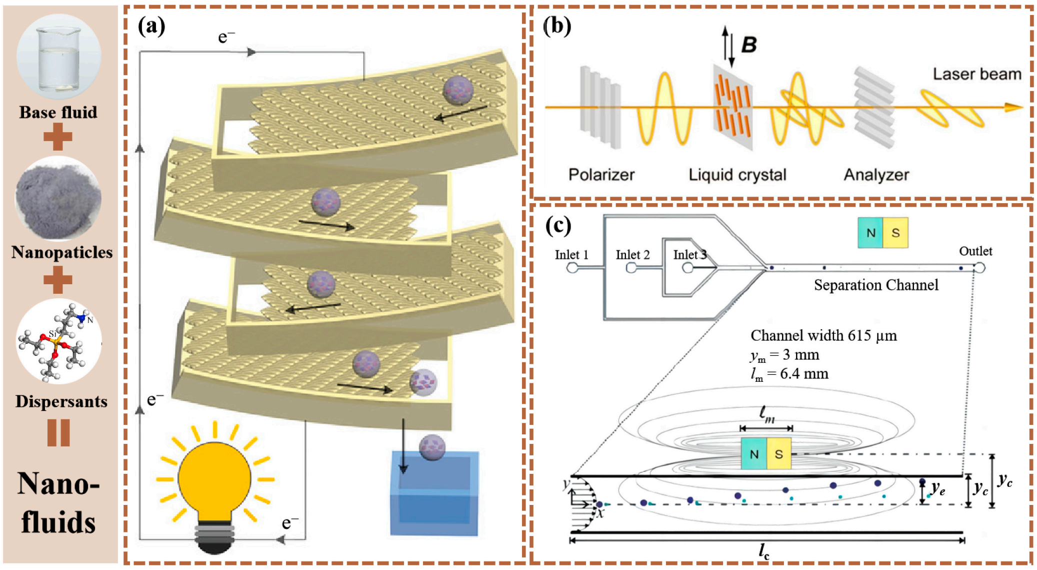

Figure 1. Schematic illustration of: (**a**) the ladder generator formed by UMNDG [8]; (**b**) process of the optical switching [9]; (**c**) microfluidic multi-target sorter [6].

Despite over half a century of study and significant advancements in magnetic nanofluids, the intriguing features and usage of these materials remain largely underexplored. Additionally, the majority of the commentaries that appeared on the subject have merely focused on the characteristics of the magnetic energies and compiled the physics equations, encompassing some facets of targeted drug transport, droplet microfluidics, and collection of power, or their uses. Therefore, a comprehensive and systematic review of the design and manufacture of magnetic nanofluids, exploring a wide range of applications, is essential in order to enlighten and assist scientists from various disciplines. In addition to discussing the most recent advancements and future orientations in ferrofluidic platform design, this paper provides a thorough overview of the uses and features of ferrofluidic platforms.

Initially, we will explore materials that are produced or composed of ferromagnetic fluids, which includes the preparation of magnetic nanofluids and their stability. An analysis is conducted on the influencing factors and physical properties of magnetic nanofluids. The application fields of magnetic nanofluids, including heat transfer enhancement, energy harvesting, and microflow control, are introduced. Lastly, we will critically evaluate the current opportunities and challenges and predict the future of ferromagnetic fluids.

2. Preparation and Stability of Magnetic Nanofluids

The present topic is not focused on highlighting the thermophysical facets of nanofluids, but rather on the characteristics of nanofluids in stable conditions. It is hoped that the discussion of the stability of nanofluids will enhance their broad suitability as much as possible. Nanofluids can be roughly divided into four categories according to the types of nanoparticles required for the synthesis: (a) metals, (b) metal oxides, (c) carbon, and (d) blended/mixed metal systems. The microstructure is shown in Figure 2. These nanoparticles will float in a base solution, including water, methanol, glycol, paraffin or transformer oil, etc. The static sedimentation rate of nanoparticles in a nanosuspension is consistent with Stokes' law, which indicates that viscous resistance, buoyancy and gravity balance have positive effects on the dispersion of nanoparticles. The following strategies may facilitate the decrease in the sedimentation rate of nanoparticles in nanosuspensions and thus improve the stabilization of the nanofluid, (a) reducing the size/radius of nanoparticles, (b) increasing the viscosity of the liquid media, and (c) minimizing the density difference between the nanoparticles and the base fluid. Changes in particle size are expected to alter the sedimentation rate of nanoparticles and thus improve the stability of the nanofluids, which is based on the conclusion that V is in proportion to the square of R. According to the theory of colloidal chemistry, when the size of the nanoparticle reaches the critical condition, there will be no sedimentation due to Brownian motion. Nevertheless, the nature of nanoparticles has higher superficial energy that could cause the occurrence of agglomeration behavior. Consequently, the fabrication of a steady nanofluid has an essential impact on the prevention of agglomeration.

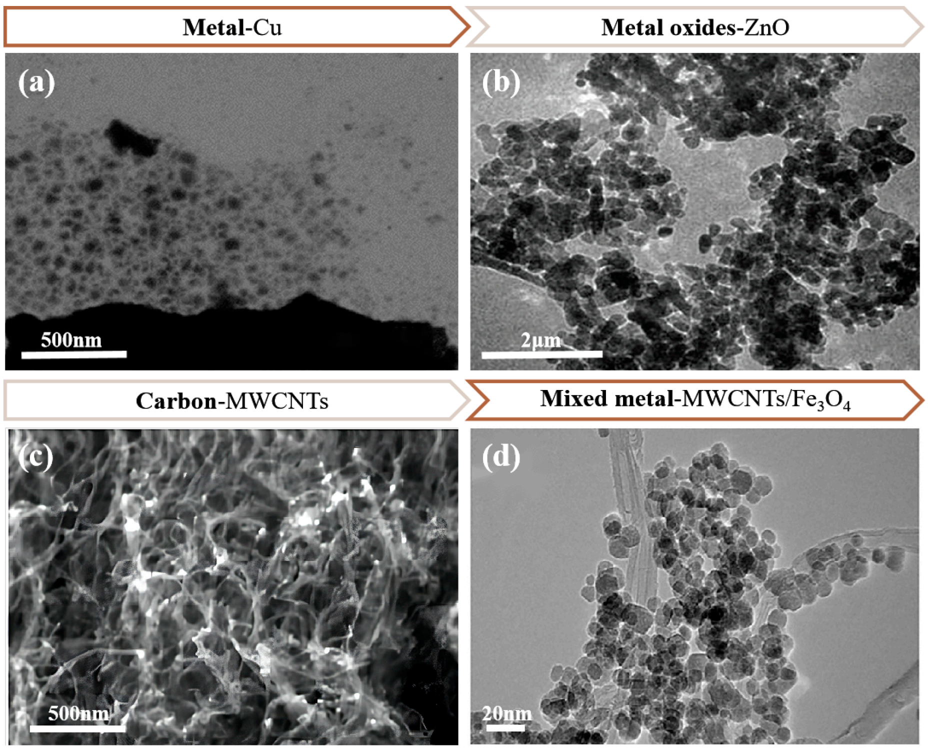

Figure 2. (**a**) Electron microscopy images of Cu NPs [10]; (**b**) TEM images of ZnO NPs [11]; (**c**) SEM images of MWCNTs [12]; (**d**) TEM images of Fe_3O_4 NPs decorated MWCNTs [13].

In this section, a thorough examination of nanofluids' stabilities is presented and reported in the following order: (a) categorization of nanofluids, (b) formulation techniques of nanofluids, (c) stabilization assessment of nanofluids, and (d) factors leading to changes in the steadiness of nanofluids.

2.1. Categorization of Magnetic Nanofluids

As a special functional material, magnetic nanofluids are a kind of uniform and stable colloid solution formed by wrapping magnetic particles of the nanometer order with a layer of long-chain surfactant and evenly dispersing them in the base liquid. Magnetic fluid is composed of magnetic nanoparticles, the base liquid, and surfactant. Depending on their magnetic nanoparticles, magnetic nanofluids can be classified into ferrite-based magnetic fluids, metal-based magnetic fluids, and iron nitride-based magnetic fluids.

2.1.1. Ferrite-Based Magnetic Nanofluids

The composite oxides composed of iron oxide and one or more other metal oxides are called ferrite. Due to the ferrite-based magnetic nanofluids' very good stability, these have become the most widely used magnetic nanofluids at home and abroad, and their disadvantage is that their saturation magnetization strength is low, which limits the scope of their applications.

2.1.2. Metal-Based Magnetic Nanofluids

Metal-based magnetic nanofluids commonly use metal nanoparticles such as Fe, Co, Ni and their alloys, etc., and their saturation magnetization strength is very high, but their chemical stability is poor, prone to oxidation deterioration, which leads to a decline in the performance of the magnetic nanofluids.

2.1.3. Iron Nitride-Based Magnetic Nanofluids

The saturation magnetization strength of iron nitride-based magnetic nanofluids is about three times higher than that of ferrite magnetic fluids, and their chemical stability is also stronger than that of metal-based magnetic nanofluids and ferrite-based magnetic nanofluids; thus, it has become a hot spot of researchers' attention. However, there is still an oxidation problem of iron nitride-based magnetic nanofluids; in the atmosphere, with the prolongation of time, their saturation magnetization strength decreases.

2.2. Formulation Techniques of Magnetic Nanofluids

2.2.1. One-Step Method for Preparation Magnetic Nanofluids

The one-step method refers to the preparation of nanoparticles while directly dispersing nanoparticles into the base solution to obtain nanofluids. This method is particularly valuable for ensuring uniformity and stability in the final suspension, as it minimizes the chances of agglomeration by directly embedding the nanoparticles in the desired medium [14]. Unlike processes that may lead to stability issues due to secondary forces, the one-step method leverages in situ generation and stabilization of nanoparticles to mitigate common challenges such as van der Waals attraction and gravitational sedimentation. This approach not only enhances the colloidal suspension's steadiness but also optimizes the functional properties of magnetic nanofluids for applications requiring consistent particle distribution and size, such as in enhanced oil recovery (EOR) in saline environments. By integrating nanoparticle creation with their dispersion, the one-step method simplifies the production process and can lead to improved performance characteristics in a variety of applications, from thermal management to biomedical fields, thus ensuring a high degree of nanoparticle dispersion and stability from the outset. Figure 3 illustrates some one-step synthesis of magnetic nanofluids.

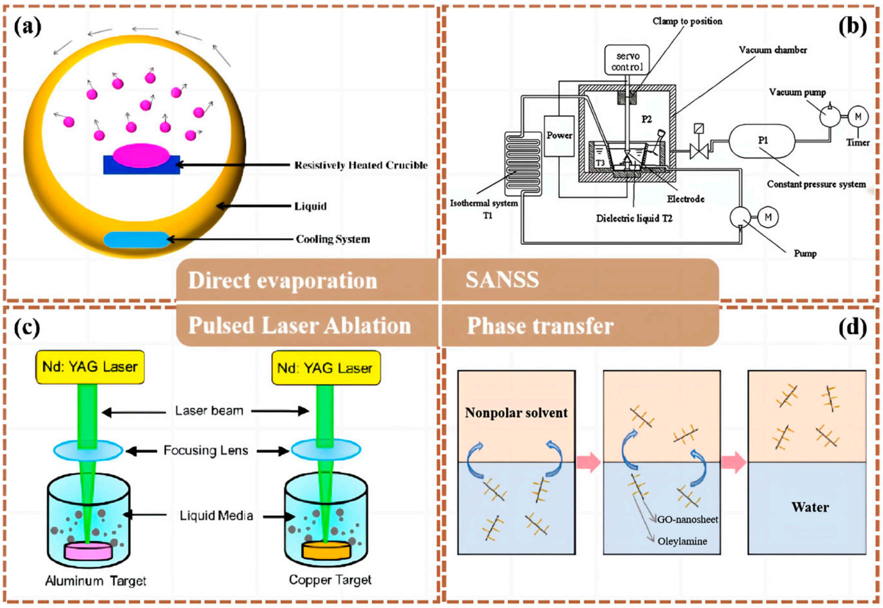

Figure 3. Schematic illustration of (**a**) direct evaporation technique [14]; (**b**) submerged arc nanoparticle synthesis system [15]; (**c**) pulsed laser ablation [16]; (**d**) phase transfer process [17].

2.2.2. Two-Step Method for Preparation Magnetic Nanofluids

The two-step method first prepares the nanomaterials through physical or chemical processes, and then by dispersing the nanoparticles in the fluid by magnetic or ultrasonic stirring, etc. The two-step method has great scalability and efficiency, including chemical coprecipitation, reduction/replacement and microwave synthesis [14]. Related studies have found that by varying the mode of the particle group, iron-magnetic particles can perform and accomplish a number of assignments, which range from traveling through tight pathways in a chain-like mode, operating other particles by gathering into ribbons in a broadly simultaneous way and loading heavy cargoes by self-organizing into swirls [18]. All such results suggest that this strategy of particles flock operation is characterized by elastic operability, high tunability and multi-functionality. The self-assembly features of magnetic nanofluids have been applied to multiple domains, including pharmaceutical transport, magnetic suspension, and photonics. Some investigators have reported the efficacy of magnetic particle accumulation in magnetic fields [19]. Figure 4 shows the process of preparing nanoparticles by chemical coprecipitation [18,19].

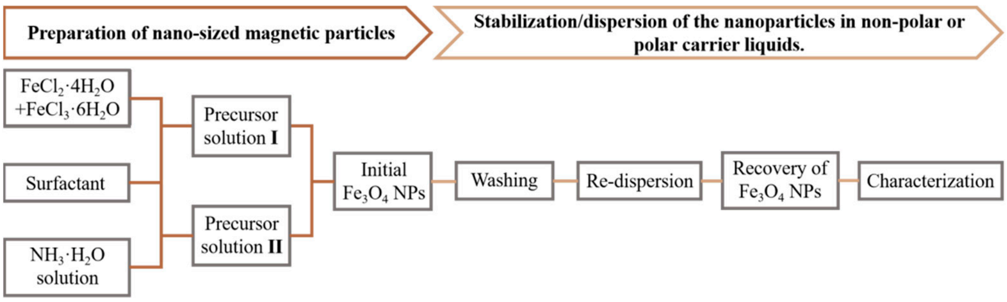

Figure 4. Process of preparing Fe_3O_4 nanoparticles by chemical coprecipitation [18,19].

2.3. Characterization of Nanofluids

The characterization of nanofluids encompasses the examination of nanoparticles alongside assessing the stability of the nanofluids. Nanoparticle characterization primarily involves scrutinizing morphology, particle size and distribution, chemical composition, surface properties, and thermal properties. Utilizing techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), and dynamic light scattering (DLS), one can ascertain the particle size and distribution of nanoparticles. Additionally, these methods enable the observation of nanoparticle morphology, including shape and surface structure. Determining the chemical composition and structure can be achieved through X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), mass spectrometry, and similar techniques. Surface properties, encompassing charge, hydrophilicity, and hydrophobicity can be evaluated via parameters like surface equipotential and surface tension. Thermal properties are typically measured using techniques such as thermogravimetric analysis (TGA) and thermal conductivity meters.

The assessment of nanofluid stability primarily encompasses evaluating sedimentation and condensation, dynamic stability, and long-term stability. It is imperative to scrutinize nanofluid stability across various temperatures, pH levels, and salt concentrations to determine potential sedimentation or coagulation under different conditions. Employing techniques like dynamic light scattering (DLS), confocal laser scanning microscope (CLSM), and others in the real-time monitoring of nanofluid particle size and distribution aids in assessing dynamic stability. Following prolonged storage, stability evaluation involves observing any changes in appearance and measuring potential alterations in particle size distribution.

2.4. Stabilization Assessment of Magnetic Nanofluids

The stability of nanofluid depends on several points [20]. (a) Nanofluids are polyphase scattered systems which have high surface energy. And they are very instable in terms of thermodynamics- (b) Nanoparticles scattered in nanofluid exhibit intensive Brownian movements. The motions of nanoparticles can counteract their sedimentation owing to the gravity. (c) Nanoparticles scattered in a liquid may precipitate over time owing to the accumulation of nanoparticles caused by van der Waals forces. (d) There is no foreseen chemical response among the suspended nanoparticles, the basic liquids and nanoparticles. Agglomeration and sedimentation are two main occurrences associated with the stabilization of nanofluids. Particle sedimentation in magnetic nanofluids may occur under the influence of magnetic fields, gravity fields or the gradients of magnetic fields because the outer magnetic field is linked straightforwardly to the dimension distribution of magnetic nanoparticles. The sedimentation of particles has a great influence on the stabilization of magnetic nanofluids. Some studies have used superparamagnetic particles to reduce the sedimentation of nanoparticles. The utilization of superparamagnetic particles in magnetic nanosuspensions is not always sufficient to establish the stabilization of magnetic nanofluids. Magnetic nanoparticles do not stabilize in the matrix fluid owing to the presence of Langton–Van der Waals forces and magnetic forces that drive irreversible agglomeration of the nanoparticles. Therefore, a repulsive power between magnetic nanofluids is inserted to counteract the dipole–dipole magnetic force and Langton–Van der Waals force. The repulsion of the nanoparticles can be achieved through the utilization of polymeric surfactants that act as an around-particle coating. It can generate entropic repulsion, or through the variation in the surface from the nanoparticles, introduce Coulombic repulsion. In general, the scattering processes of magnetic nanofluids are undertaken by ultrasonic homogenization with the existence of surfactants. Agglomeration and deposition of particles can contribute to higher stickiness, higher pumping fees, and lower heat performances. These may have a disadvantageous effect and consequences on their relevant suitability.

2.5. Factors Leading to Changes in the Steadiness of Magnetic Nanofluids

Particular attention is paid to the issues of nanofluids' steadiness in various handling environments, including elements such as temperature requirements, mobility conditions, outer magnetic fields, wall effects and shear forces. The focus of this research exploration is to establish and provide an interpretation of the diverse elements (dielectric constant of the base liquids, zeta potential, pH, particle dimensions, form and density, etc.) that may have a detrimental impact on the stabilization of nanofluids [21].

2.5.1. Temperature

Temperature plays a pivotal role in influencing the stability of magnetic nanofluids. As temperature increases, the kinetic energy of nanoparticles also rises, leading to enhanced Brownian motion. This intensified movement can counteract sedimentation to some extent but also increases the risk of agglomeration due to elevated collision rates among particles. Furthermore, temperature variations affect the viscosity of the base fluid, which in turn influences the suspension's stability. The thermal expansion coefficient disparity between the nanoparticles and the base fluid under varying temperatures can also induce thermal stress. In high temperature applications, thermal stress can negatively affect the stability of nanofluids [14].

2.5.2. Mobility Conditions

Mobility conditions, encompassing the flow and distribution of magnetic nanofluids within a system, significantly affect their stability. Under laminar flow conditions, nanoparticles tend to distribute evenly, maintaining stability. However, in turbulent flow conditions, the erratic movement can lead to uneven distribution and increased particle–particle interactions, fostering agglomeration. Additionally, the rate of flow impacts the shear stress experienced by the nanoparticles, influencing their alignment and dispersion. Optimal migration conditions are essential to prevent deposition and ensure uniform distribution of nanoparticles, which is conducive to improving the sustained thermal properties of magnetic nanofluids. [17].

2.5.3. Magnetic Fields

In pharmaceutical transport, magnetic suspension, photonics, and drying applications, magnetic-field-induced particle accumulation is advantageous. The convective thermal conductivity may increase or reduce in the presence of an imposed magnetic field owing to the following elements: the first is the magneto-to-inertial strength ratio, and the second are the chain-like agglomeration creation and the rise in the partial thermal conductivity of the magnetic nanofluids. CuO nanofluids were able to lose steadiness at a quicker velocity with the influence of a strong magnetic field. With the effect of a powerful magnetic field, the average particle dimensions become larger, while the zeta potential level falls, illustrating the trend of accumulation and poor steadiness [22]. The settling rate of all floating particles becomes apparently quicker in the effect of a perpendicular magnetic field. The formation of chain-like constructions in Fe_3O_4/SiO_2 nanofluid at constant magnetic fields is concluded. Magnetic nanoparticles ought to keep their steadiness after removing the enforced magnetic field. Electrostatic or three-dimensional stability techniques must be implemented to keep the stability and repetitive utilization of magnetic nanofluids. Some researchers take oleic acid as a dispersant to keep the stability of magnetic nanoparticles.

2.5.4. Wall Effects

The interaction between nanoparticles and the container or system walls (wall effects) can markedly influence the stability of magnetic nanofluids. These effects include nanoparticle adsorption on the walls, leading to a concentration gradient, and potentially initiating agglomeration near the walls. Furthermore, wall roughness and material properties can alter the flow dynamics near the boundary, affecting nanoparticle dispersion. The electrostatic interactions between the charged walls and nanoparticles also play a significant role, with attraction leading to accumulation, and repulsion enhancing dispersion. Understanding and managing wall effects are crucial for maintaining the stability and homogeneity of magnetic nanofluids in confined spaces [23].

2.5.5. Shear Forces

Shear forces, arising from fluid motion or external agitation, have a dual impact on the stability of magnetic nanofluids. On the one hand, moderate shear forces can prevent sedimentation and promote uniform dispersion by overcoming attractive forces between nanoparticles. On the other hand, excessive shear can induce particle agglomeration by enhancing collision rates and energy transfer among nanoparticles. The balance between dispersing and agglomerating forces under shear forces is delicate and depends on factors like particle size, concentration, and the presence of surfactants. Appropriately managed shear forces can thus be a tool for enhancing nanofluid stability, but they require careful control to avoid destabilizing effects [24].

3. Physical Properties of Magnetic Particles and Nanofluids

3.1. Density of Magnetic Nanoparticles and Nanofluids

The exploration of magnetic nanoparticles and their nanofluids in physical properties—particularly in terms of density—is important for understanding their interactions in suspensions and behavior under external magnetic fields. This deep understanding of the various factors affecting density and how density influences the flow behavior, stability, and magnetic field response of nanofluids provides significant guidance for the design and development of novel nanomaterials and the applications.

The composition and size of magnetic nanoparticles are the main factors affecting their density. The atomic mass and lattice structure of the materials constituting these nanoparticles directly determine their density, where heavier materials such as iron, cobalt, and nickel lead to nanoparticles with higher densities. For instance, ferrite (Fe_3O_4) nanoparticles typically have a higher density than silicon (Si)-based nanoparticles. Additionally, the size of the particles, particularly their surface-area-to-volume ratio, plays a crucial role in determining the density within the fluid medium. Due to the larger surface-area-to-volume ratio, smaller nanoparticles exhibit unique behaviors (such as increased surface energy and quantum size effects) that can significantly affect the overall density of nanofluids. Studies on the assembly of magnetite nanoparticles have shown that their size and the resulting magnetism when they self-assemble into layers on magnetic templates can affect their density distribution.

The concentration of magnetic nanoparticles in nanofluids is another key factor in altering the overall density. Increasing the concentration of nanoparticles can enhance the performance of the fluid [25], but at higher nanoparticle concentrations, particle agglomeration increases, which increases the agglomeration size and thus the risk of sedimentation. Therefore, a balance must be found between enhancing the performance of nanofluids and maintaining their stability. Effective surface modification techniques and dispersants can improve the dispersibility of nanoparticles, while ultrasonic dispersion techniques can be used to prevent particle aggregation, thereby maintaining the uniformity and stability of nanofluids [26].

The density of magnetic nanofluids significantly affects their flow behavior and stability. Density gradients in magnetic nanofluids can lead to natural convection, significantly affecting the suspension's stability. For example, studies on the colloidal stability of aqueous ferrofluids under high magnetic fields have shown that stability is influenced by the concentration of nanoparticles and magnetic coupling energy.

3.2. Thermal Conductivity of Magnetic Nanoparticles and Nanofluids

Compared to traditional heat transfer fluids, nanofluids exhibit great potential in heat transfer applications due to their unique thermophysical properties. In thermal transfer applications, the thermal conductivity of magnetic nanoparticles and their nanofluids is a crucial physical parameter. This thermal conductivity not only determines the efficiency of materials in transferring heat but also has significant implications for designing high-performance cooling systems, improving the efficiency of energy devices, and developing new thermal management technologies.

Factors affecting thermal conductivity include the size, shape, and distribution of nanoparticles in the base fluid. Nanoparticles of smaller sizes offer a larger surface area, providing more heat exchange surfaces, thereby helping to improve thermal conductivity. The shape of nanoparticles (such as spherical, rod-like, or plate-like) also affects the path and efficiency of heat transfer within the material, with different shapes exhibiting distinct characteristics in thermal conduction. Moreover, ensuring the uniform distribution of nanoparticles in the base fluid is equally important for efficient heat transfer, as uneven distribution may lead to reduced thermal conduction efficiency.

The properties of the base fluid and the material of the nanoparticles are key factors determining thermal conductivity. Different base fluids (such as water, oil, or ethylene glycol) and different types of nanoparticles (such as ferrites, silver, or copper nanoparticles) can cause significant differences in the thermal conductivity of nanofluids due to their inherent thermophysical properties, as shown in Figure 5. The interaction between nanoparticle materials and the base fluid is crucial for adjusting and optimizing the thermal conductivity of nanofluids.

Magnetic fields are an effective means to enhance the thermal conductivity of nanofluids. By applying an external magnetic field, it is possible to influence the orientation and distribution of nanoparticles, thereby altering the macroscopic thermal conduction characteristics of the nanofluid. Magnetic fields can induce the nanoparticles to form ordered structures, which can serve as effective channels for heat transfer, thus improving thermal conductivity [27]. Furthermore, magnetic fields can also dynamically regulate the thermo-physical properties of nanofluids, providing a flexible adjustment mechanism for thermal management systems. Predicting thermal conductivity poses challenges for their application. Prediction models based on neural networks can accurately predict the thermal conductivity of mixed nanofluids with various nanoparticle combinations, offering potential for heat transfer applications [28].

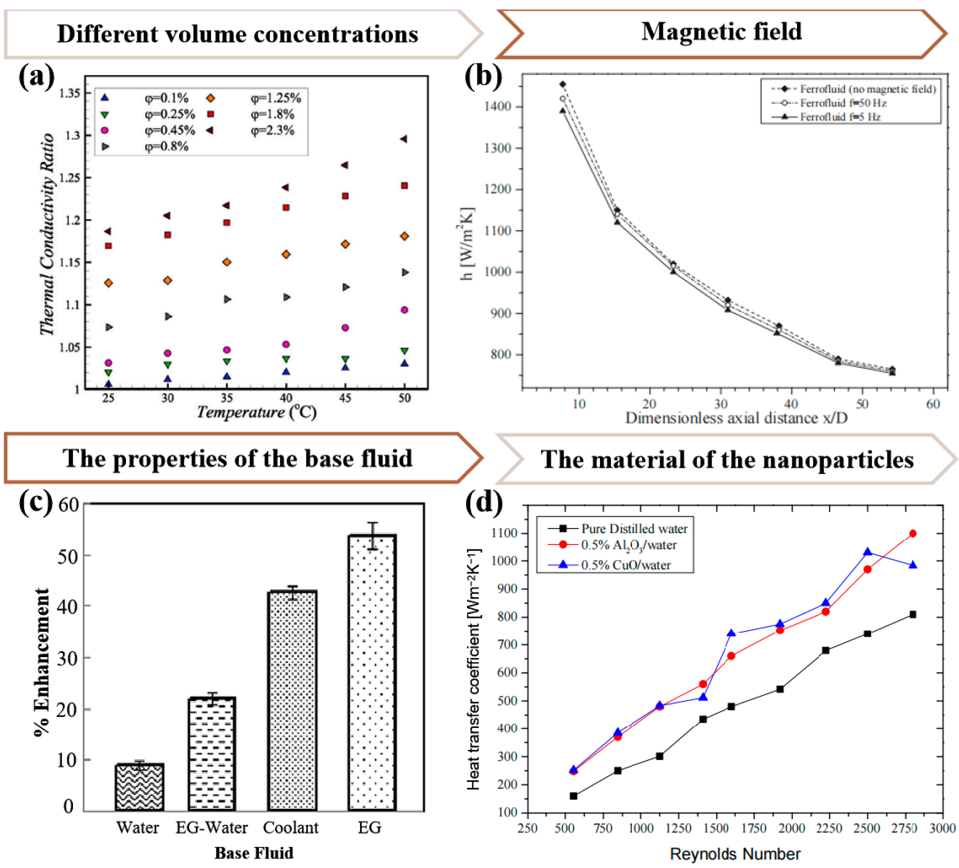

Figure 5. Comparison of (**a**) thermal conductivity of EG-based F-MWCNT-Fe_3O_4 hybrid nanofluids with different volume concentrations; (**b**) heat transfer coefficient of magnetic nanofluids at 1 vol. % concentration with and without magnetic field [29]; (**c**) effect of different base fluid on the enhancement in overall heat transfer coefficient [30]; (**d**) convective heat transfer coefficient according to Re of distilled water and 0.5 vol% loading of Al_2O_3 and CuO nanopowder in water [31].

3.3. Magnetism Properties of Magnetic Nanoparticles and Nanofluids

Magnetic nanoparticles and nanofluids, due to their unique magnetic properties, hold a fundamental and significant place in various applications from medicine to engineering. These magnetic characteristics enable the manipulation of magnetic nanoparticles and nanofluids under the control of external magnetic fields, thus making the understanding and control of these properties crucial for optimizing the functionality and efficiency of magnetic nanoparticles and nanofluid technologies. The magnetic qualities of these materials, such as saturation magnetization, coercivity, and remanence, not only offer possibilities for improving existing technologies but also pave the way for novel applications [32]. The saturation magnetization of magnetic nanoparticles is a key factor affecting their performance in applications such as magnetic separation and magnetic resonance imaging; the level of coercivity determines the potential application of magnetic nanoparticles in data storage, while the magnitude of remanence affects the magnetic performance of magnetic nanoparticles in the absence of an external magnetic field, which is vital for long-term application scenarios.

Adjusting the magnetic field strength and direction enables the behavior of magnetic nanoparticles, such as guided motion and formation of specific structures, to be precisely controlled. This control capability provides a technical basis for the use of nanofluids in targeted drug delivery and microfluidic devices [33]. External magnetic fields can modify the magnetism of magnetic nanoparticles and nanofluids, thereby enhancing their functionality in applications like magnetic hyperthermia and targeted drug delivery. Field-induced assembly of magnetic nanoparticles into chain-like structures can significantly affect the macroscopic properties of nanofluids, such as viscosity and thermal conductivity, thereby improving the efficiency of heat transfer applications.

In the medical field, magnetic nanoparticles are widely used in imaging, therapy, and diagnostics due to their controllable magnetic properties. Magnetic nanoparticles with controlled magnetism can be used for targeted drug delivery and enhancing the contrast in magnetic resonance imaging, while cobalt-doped magnetite nanoparticles can enhance cancer treatment through magnetic hyperthermia [34]. In energy conversion, the magnetism of magnetic nanoparticles can be used to control the flow of nanofluids in heat pipes through magnetic fields, optimizing thermal management systems [35]. In environmental management, the magnetic properties of magnetic nanoparticles enable rapid, efficient separation and recovery in water treatment and pollutant removal processes [36]. The ability to control the magnetism of nanoparticles enables the development of more efficient and targeted technologies.

3.4. Optical Properties of Magnetic Nanoparticles and Nanofluids

Magnetic nanofluids exhibit unique optical properties that significantly influence applications across various fields. These properties, including absorption, scattering, and photoluminescence, are not only crucial for understanding optical phenomena at the nanoscale but also have significant implications for developing new medical treatment technologies and improving the performance of optoelectronic devices.

The morphology of nanoparticles, including their size and shape, is a key factor determining their optical performance. Variations in particle size can affect their absorption and scattering spectra and may also change the efficiency and wavelength of photoluminescence. For instance, smaller nanoparticles might exhibit different light absorption and emission characteristics due to quantum size effects compared to larger particles. Additionally, the shape of nanoparticles (such as spherical, rod-like, or cubic) significantly influences their optical behavior, with nanoparticles of different shapes showing distinct optical responses due to their unique surface plasmon resonance characteristics. Studies have shown that metallic nanoparticles, especially gold and silver, can have their optical properties tailored through colloidal chemistry methods to enhance surface plasmon resonance.

The optical properties of magnetic nanoparticles and nanofluids have a wide range of applications. Nanofluids demonstrate promising optical characteristics and potential for use as electromagnetic wave absorption media in solar collectors and reservoirs [37]. These nanoparticles can absorb specific wavelengths of light and interact with light through scattering and photoluminescence. The light absorption characteristics are a key factor in imaging and phototherapy applications, where magnetoplasmonic Fe_3O_4/TiN nanofluids can effectively absorb full-spectrum solar energy and control their photothermal performance through an external magnetic field. Simultaneously, the scattering properties of magnetic nanoparticles are also crucial for optical imaging technologies, where their scattering behavior can enhance image contrast and improve imaging quality. Additionally, some magnetic nanoparticles exhibit photoluminescence, making them widely applicable in fields like fluorescence labeling and bioimaging.

By deeply understanding and leveraging the materials' light absorption, scattering, and photoluminescence properties, along with precise control over their size and shape, it is possible to design optical materials and devices with improved performance and a broader range of applications. With advances in nanotechnology and materials science, the potential of magnetic nanoparticles and nanofluids in optical applications will be further explored and utilized.

3.5. Viscosity of Magnetic Nanoparticles and Nanofluids

Magnetic nanoparticles and their dispersions in fluids, forming nanofluids, play a crucial role in the fields of flow and heat transfer, where their viscosity properties have a direct impact on the efficiency of these processes [38]. Viscosity not only determines the pumping force required for the fluid to flow through pipes but also affects the efficiency of heat transfer within the fluid. Therefore, understanding and controlling the viscosity of nanofluids is vital for designing efficient cooling systems and optimizing thermal energy management strategies [39]. The viscosity of nanofluids is influenced by several factors. First, viscosity is closely related to the concentration of nanoparticles; as the concentration of magnetic nanoparticles in the base fluid increases, the viscosity typically rises. This change significantly affects the fluid's flow performance and heat transfer characteristics. Second, viscosity is also strongly dependent on temperature; generally, the viscosity of nanofluids decreases with an increase in temperature, which facilitates fluid flow and more efficient heat transfer. Additionally, under the influence of an external magnetic field, nanofluids may exhibit thixotropic behavior, meaning their viscosity changes with the shear rate. This property allows for a high degree of controllability of magnetic nanoparticles nanofluids in specific applications. The size and shape of nanoparticles also significantly affect the viscosity of nanofluids. Smaller particles typically lead to lower viscosity due to reduced inter-particle friction. Non-spherical particles can increase viscosity because they tend to align and interact in more complex ways within the fluid. The viscosity of magnetic nanoparticles' nanofluids has profound implications for their practical applications. Nanofluids with high viscosity require greater pumping power to maintain flow, directly impacting the system's energy efficiency. In thermal management and cooling systems, optimizing viscosity is key to achieving efficient heat transfer. By precisely controlling the concentration of nanoparticles and utilizing the effect of temperature on viscosity, nanofluids can be designed to transfer heat effectively while being more economical in terms of energy consumption. Meanwhile, the impact of external magnetic fields on the viscosity of nanofluids opens new possibilities, making it a reality to dynamically regulate fluid properties by adjusting the magnetic field strength, which is especially important in high-tech applications that require precise control of flow and heat transfer conditions [40]. Conducting in-depth research on the behavior of viscosity and the mechanisms through which it is influenced by nanoparticle concentration, temperature, and external magnetic fields provides powerful guidance for the design and application of nanofluids. Figure 6 showed the study on the physical property of magnetic nanofluids. This can lead to breakthroughs in enhancing energy efficiency, optimizing thermal management, and developing new dynamic control systems.

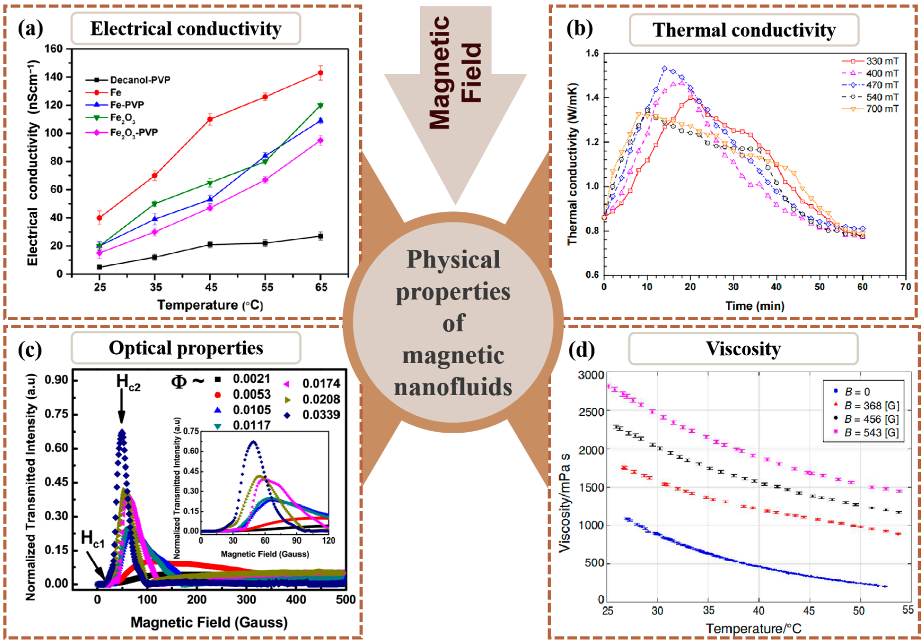

Figure 6. (**a**) Electrical conductivity of Fe, Fe-PVP, Fe_2O_3, and Fe_2O_3-PVP nanofluids [41]; (**b**) effect of magnetic field intensity at 25 °C on the thermal conductivity of Fe_3O_4-CNT/water with time [29]; (**c**) transmitted intensity vs. field intensity for magnetic nanofluid with different particle concentrations [42]; (**d**) change in viscosity with temperature under different magnetic field intensity [43].

3.6. Specific Capacity of Magnetic Nanoparticles and Nanofluids

Magnetic nanoparticles and their constituent nanofluids have demonstrated significant potential for applications in thermal energy storage and transfer. The specific heat capacity is one of the key physical parameters influencing their performance, which determines the material's ability to store and release thermal energy. Determining the specific heat capacity primarily involves considering the material, size, and composition of nanoparticles. Different nanoparticle materials possess different heat capacity values, directly affecting the overall specific heat capacity of the nanofluids [4]. Moreover, research has shown that smaller nanoparticles exhibit unique thermal performances due to increased surface-area-to-volume ratios and quantum effects, influencing their heat storage and transfer capabilities. Additionally, the composition of the nanofluid, namely the specific heat of the base fluid and the concentration of nanoparticles, further determines the system's thermal response characteristics. Adjusting these parameters allows for the customization of nanofluids for specific thermal applications, balancing thermal capacity and other thermal physical properties to enhance thermal energy storage and transfer efficiency. To enhance the specific heat capacity of magnetic nanofluids, external magnetic fields can be utilized to improve the thermal capacity performance of the nanofluids. Magnetic fields can affect the arrangement and distribution state of the nanoparticles, thereby influencing the fluid's thermal–physical properties. By precisely controlling the strength and direction of the magnetic field, the specific heat capacity of the nanofluids can be regulated to some extent, optimizing the thermal energy storage and transfer processes [44]. Furthermore, the uniform dispersion and stability of nanoparticles in the base fluid are crucial for maximizing the effective specific heat capacity of nanofluids. Exploring techniques to improve dispersibility and stability, such as ultrasonic treatment and the use of surfactants, is essential for maintaining better thermal performance over time. Delving into the factors that affect specific heat capacity and employing enhancement strategies such as magnetic field control can significantly improve the performance of nanofluids in thermal energy storage and conversion systems. With deeper research into the thermal properties of these materials, more innovative applications are expected in the areas of energy efficiency improvement, environmental protection, and the development of new energy technologies.

4. Design and Applications of Magnetic Nanofluids

4.1. Enhanced Heat Transfer of Magnetic Nanofluids

The fluidity characteristics, thermal features and thermo-magnetic convection characteristics of magnetic nanofluids create a good cornerstone for enhancements in heat transfer performance. Factors affecting the thermal transfer of magnetic nanofluids include the magnetic field strength, the frequency, the direction, the volumetric fraction and the flow rate of the iron-magnetic liquid, etc., all of which are crucial elements in deciding the thermal transfer efficiency. Meanwhile, the appropriate modification and doping of magnetic nanofluids may boost the thermal transfer performance of magnetic nanofluids. For instance, the lauric-acid-coated magnetic nanofluids and grapheme oxide Fe_3O_4 mixed magnetic flow [45] show an excellent performance of enhancing thermal transfer and potential for the development of magneto-thermal project systems. The thermophysical characteristics of magnetic nanofluids have been investigated and analyzed. It was concluded that the use of outer magnets, along with their variations in construction, such as the creation of chain-like constructions, are among the valid elements to improve heat conduction. The effect of the chain aggregates of magnetic nanoparticles on the heat transfer of magnetic nanosuspensions under the application of a magnetic field was investigated by Nkurikiyimfura et al. [46]. They observed a remarkable increase in the heat transfer rate owing to the development of chain-like agglomeration of magnetic nanoparticles with the existence of a magnetic field that runs parallel to the thermal gradient. The findings indicated that the aspect ratio of chain-like agglomerates of magnetic nanoparticles could effectively help enhance the anisotropic heat transfer performance. Parekh and Lee also suggested that the improvement in the heat transfer rate of magnetite nanofluid in the conditions of magnetic field existence at a volume level of 4.7% was about 30%, which might be caused by the constant formation of three-dimensional zipper-like constructions of nanoparticles in magnetic liquids [47]. Asfer et al. investigated the impact of magnets on convection thermal transport of Fe_3O_4/water nanofluid in stainless metal heating pipes under laminar fluids [48], as shown in Figure 7c–e. The enhancement in partial heat transfer of Fe_3O_4/water nanofluid was attributed to the clusters of chained iron oxide nanoparticles (IONPs), which appeared inside the Fe_3O_4 nanofluid in the presence of a magnetic field. The forced convective thermal transmission of Fe_3O_4 magnetic nanofluids in a constant magnetic field was studied [49]. The mean convection thermal conductivity of magnetic nanofluids with a density of 0.25 vol.% increased by 35% compared to that of the foundational liquid at static magnetic fields generated by three magnets. Ghofrani et al. carried out an examination of the laminar by imposing convection thermal conductivity of Fe_3O_4 magnetic nanofluids with an alternative magnetism [50]. The device diagram and the enhancement in heat transfer by ferrofluid are shown in Figure 7a,b. The mean convection thermal conductivity increased by 27.6% $\pm$ 1.22% at intermediate frequency terms (50 Hz), which was attributed to attached and unattached magnetic fields. At intermediate magnetic rates, the staggered magnetic field is more valid; yet, at high-frequency states, the discrepancy in convection thermal conductivity between intermediate and low frequencies reduces. The findings indicate that partial convective thermal transport is enhanced at a lower distance from the access area and mid-magnetism frequencies. Additionally, with small-sized nanoparticles, the changes in convective thermal transmission directly influence the evolution of the heat conduction and stickiness of the nanofluid and alter their thermo-hydraulic properties. In addition, the shapes of nanoparticles also influence the heat conduction and stickiness of the nanofluid. According to previous research, the stronger the magnetic field and nanoparticles' intensity, the larger the convective thermal conductivity will be. With the increase in Re, the coefficient of convective thermal conductivity presents diverse outcomes. A number of studies suggested that the influence of magnetic field on enhancing the heat properties of hybrid nanofluid relies on both magnetic and heat performances. The findings of recent studies showed that the changes in the convective thermal characteristics of nanofluids are highly complicated.

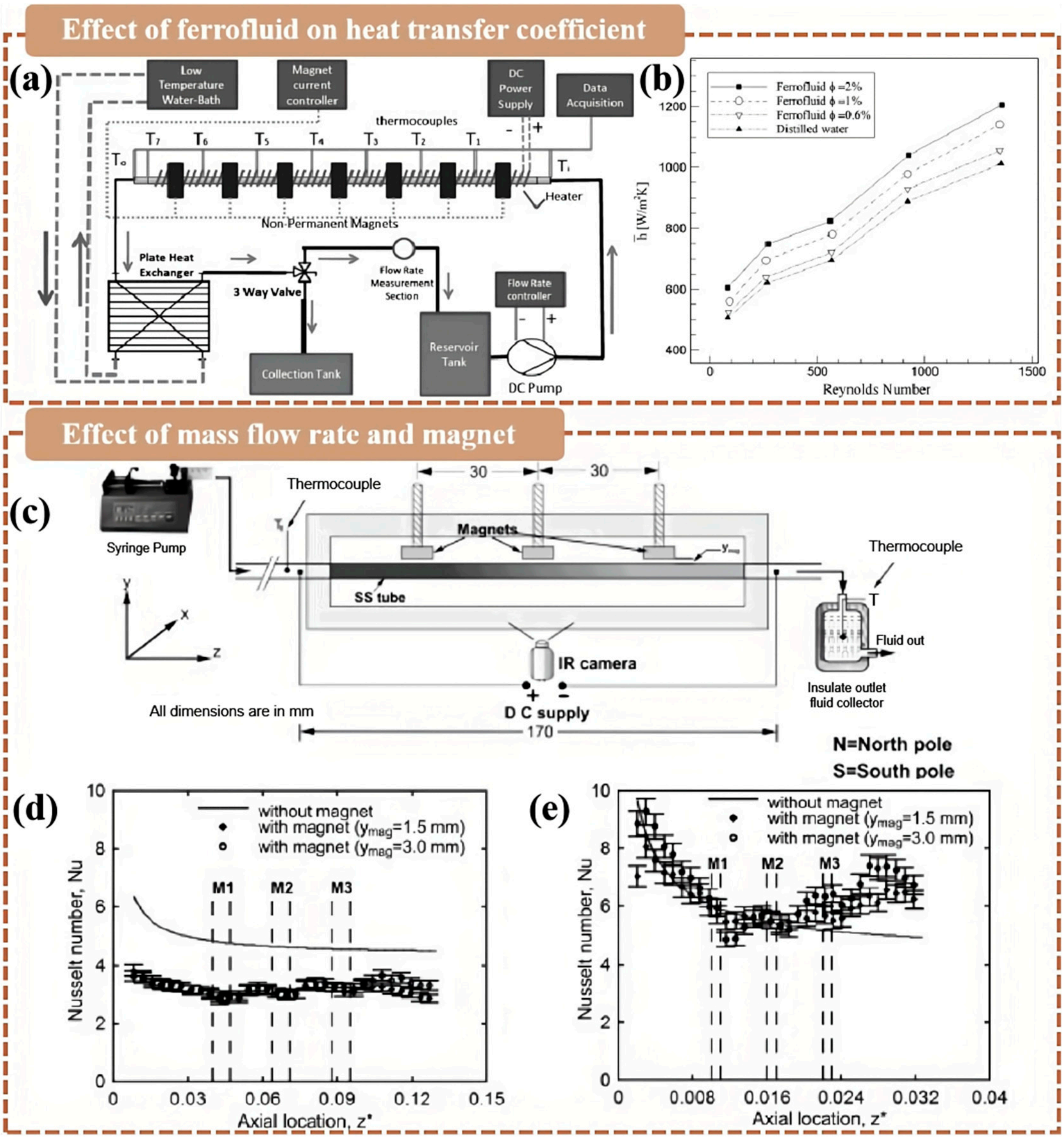

Figure 7. Enhanced heat transfer of magnetic nanofluids: (**a**) schematic of the experimental setup; (**b**) ferrofluid and distilled water average convective heat transfer variation with Reynolds number and volume concentration [50]; (**c**) schematic of the experimental setup; (**d**,**e**) variation in Nusselt number with mass flow rate: (**d**) Q = 10 μL/min (**e**) Q = 40 μL/min [48].

In addition, the influence of the size of the particles on the fluid flow and thermal transfer of magnetic nanofluids was assessed in this study. The corresponding numerical models were developed, and the calculation formulas and equations were presented, and the findings were analyzed to verify the consequences. A numero-value investigation of the heat property and pressure drop measurement of CuO-water nanofluids in ladder-shaped micro-channels showed that the voltage drop increased from 3% to 15% as the size of nanoparticles (100–200 nm) rose, while the mean Nusselt count reduced by 5.3%. Larger grain dimensions in micro-channels imply a larger voltage drop and lower heat properties. Sarafraz and his colleagues investigated the fitness of grapheme–water and grapheme–water/glycol (60:40) nanofluids in mini-channels and summarized the changes in the index of heat properties at an increasing voltage drop, rubbing ratio and pumping expense [51]. These studies indicated that the vital influence of fluid velocity and grain intensity are, on the whole, heat properties of nanofluids within micro-pathways.

The heat exchanger diagram is shown in Figure 8. Scaling is a problem that must be considered in the manufacture of efficient heat exchangers [52]. And in certain situations, it may also contribute to the stoppage of thermal converter fabrication. It was found that the fouling-induced heat rejects were closely linked to the operation time and nanoparticle density. Longer running time and particle density resulted in larger heat resistance in dirt. Consequently, new approaches of the problems have been presented by relevant researchers. The variations in fluid rheological characteristics and the utilization of active thermal transfers can effectively surmount such problems. They are solved by keeping laminar sub-layers from developing and adding to the quantity of interferences, adding to the overall surface of effective thermal transmission, creating swirl or second flow, and blending the fluids much better. Due to the vital importance of thermal converters in various aspects of manufacturing, including thermal resources, fabrication procedures, conveyance, electronics, etc., a number of ways were put forward to enhance the thermal transport capacity in these procedures, largely on the basis of structural variations in the device, like adding hot surfaces (fins), hot surface shaking, liquid input or intake, and the use of electric or magnetic fields. But these methods are inadequate to cope with the rising need of thermal transfer and compression in high-power processing installations. Using nanofluids consisting of extremely fine-grained metallic or non-metallic mixtures, the heat properties are superior to those of pure liquids. Consequently, based on earlier studies, the issue of majority of devices, like thermal converters, is their relatively low efficacy. Yet, their efficacy can be boosted through the utilization of nanofluids.

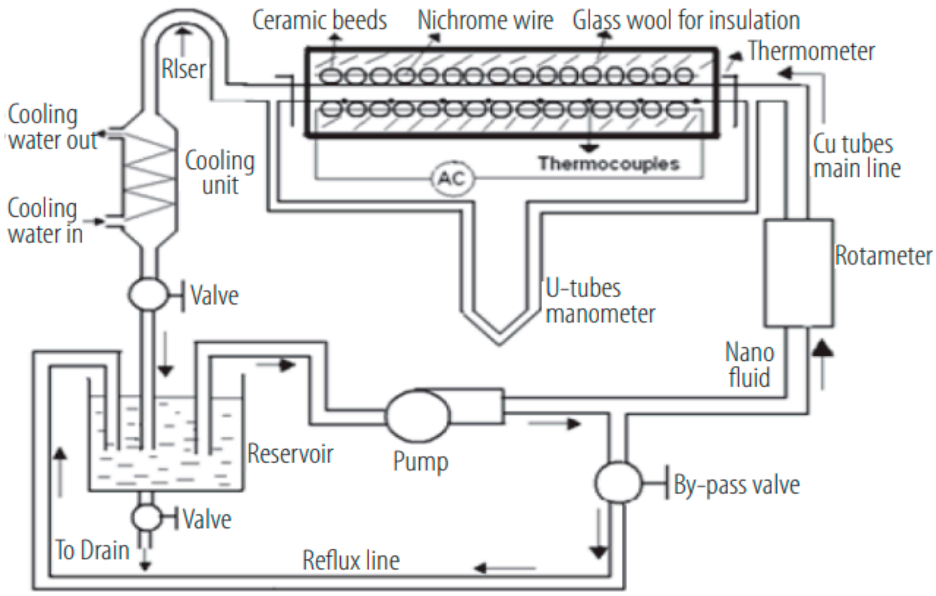

Figure 8. Schematics of a thermal exchanger [31].

4.2. Ferrofluid Based Energy Harvester

In a classic magnetic nanofluids' power collector, the shaking of the magnetic nanofluids or air liquid droplets soaking in the magnetic nanofluids may cause a time changing magnetic flux, and according to electro-magnetic sensing, an electrical current and voltage is then produced in an outer wire coil. In this way, mechanical motion energy is directly transformed into electric energy. The mechanical movement energies are straightforwardly changed into power during this course. For example, a retrofit device such as the turboelectric nano generator (TENG)-electromagnetic generator (EMG) based on magnetic nanofluids is proposed by Seol et al. concerning a magnetic nanofluids' power collector [53]. On the one hand, the outer shaking prompts the magnetic nanofluids in the vessel to slide and rub and touch the side walls of the vessel repeatedly. Due to the phenomenon of electrostatic sensing, this constant rubbing results in an inequality of the electric charge concentration between the outer poles, thus continuously creating an alternating current. In such circumstances, the combined system performs just like a TENG. On the other hand, the wobbling of the magnetic nanofluids introduces a shift in the magnetic dipole direction and a time changing flux that goes along with it. The time changing flux creates power, and therefore the blended system EMG comes into playing. It is indicated that the blended system generates a regular output sinusoidal message in both the TENG mode of operation and the EMG mode of operation, demonstrating the good performance of the device in fine and non-regular shaking acquisition. Huang et al. [8] designed an underwater magnetic nanofluid droplet generator (UMNDG), as shown in Figure 9. This study provides a new way to convert the sliding energy of the nano-magnetic droplet into electrical energy.

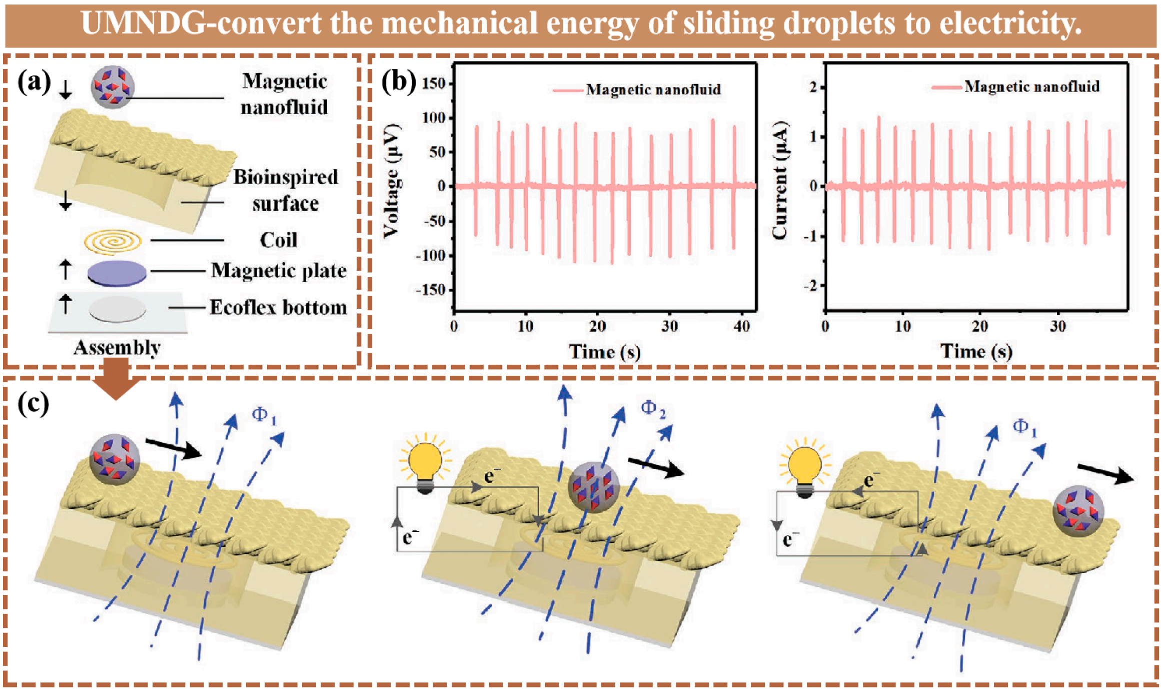

Figure 9. (**a**) UMNDG assembly diagram; (**b**) voltage and current output when 80 μL magnetic nanofluid droplets slide on the surface of the UMNDG. (**c**) Schematic diagram of magnetic nanofluid droplets sliding on the surface of UMNDG [8].

In recent years, a great concern about the growth of micro-electro-mechanical regimes (MEMS) and miniature regimes has occurred. There has been an effort to lower the consumption of power in these instruments from the milli-watt level to the micro-watt level. Currently, the electro-magnetic generator obtains its oscillating power with the sliding of a bar of iron fluid. In the presence of a magnetic field, the iron fluid is intensively magnetized. An iron liquid is a steadily suspending solution containing a blend of magnetized nanoparticles in traditional carrier liquids (e.g., water or oil). Typically, the nanoparticles are iron or iron-magnetic grains < 10 nm in size in terms of diameter and painted with a surfactant level of 1–2 nm. What distinguishes magneto-rheological liquids from iron rheological liquids is the scale of the particles. The output voltages of the collectors grow with the acceleration level, yet the level of the liquid pillar showed very little influence on the outputs. Alazmi et al. have researched the oscillating movement of the iron liquid and came to the conclusion that the oscillating movement of the magnetized nanofluid generates a timing-dependent magnetic flux, and this can lead to an electro-magnetic field in the loop. Seol et al. have researched the iron-fluid based on oscillating power harvesting for the turboelectric-EM mixed generator. A vast number of investigations have been conducted on traditional electro-magnetic power collectors in which strong magnets are utilized to produce an electrical potential. Extensive research on iron-fluid-based electro-magnetic power collectors is required in the future to conquer the existing problems and constraints in current power collectors.

4.3. Magnetic Microfluidic Applications

Microfluidics is an up-and-coming technique used for dealing with few fluids and is fundamentally classified into continuous fluid microfluidics and digital microfluidics. By bringing magnetic nanofluids into microfluidics, it helps to promote blending, pumping, focalization, separation, liquid droplet creation and shifting behaviors in sequential flow microfluidics, and it is effective to fulfill long-range, powerless and versatile manipulations in digital microfluidics. Magnetic nanofluids offer a robust instrument for liquid and droplet operations that can be used in diverse domains such as bio-sensing [54], chemistry synthesis [55], diagnostics and treatments [56,57] in medicine [58]. Figure 10 shows some applications of magnetic nanofluids.

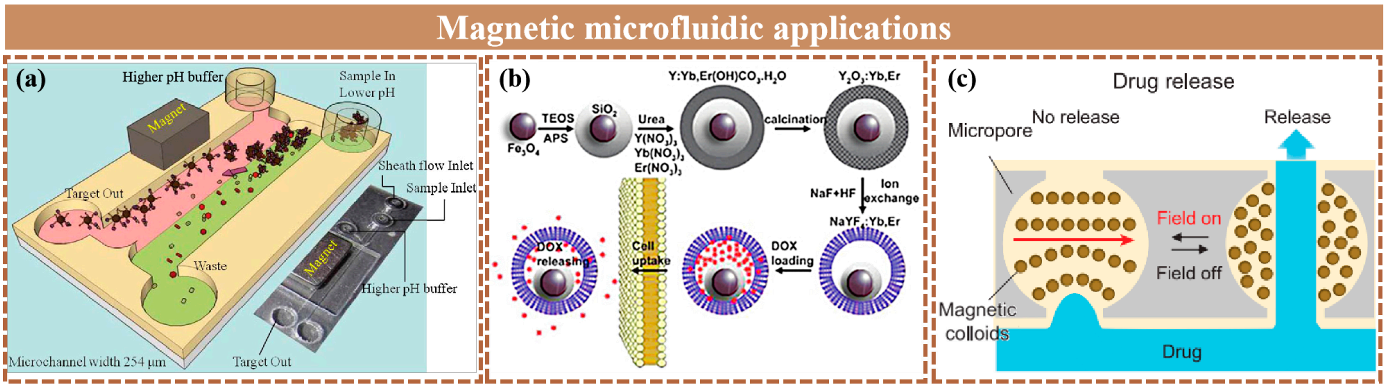

Figure 10. (**a**) Schematic diagram of target analyte separation in a microfluidic channel [6]; (**b**) schematic illustration of the synthetic procedure for the DOX-loaded Fe_3O_4@SiO2@α-NaYF/Yb [59]; (**c**) remote regulation of drug release [60].

4.4. Other Applications of Nanofluids

Magnetic nanofluids exhibit significant potential across various applications including energy storage, catalysis, and environmental purification. Concerning energy storage, the incorporation of magnetic nanoparticles into electrodes or electrolytes enhances ion transport dynamics and diminishes internal resistance, thereby elevating energy density and improving charge and discharge efficiency. For instance, Dubal et al. [61] synthesized stable nanocomposites by combining graphene oxide and polyoxometalates for electrochemical energy storage. Additionally, their development of low-viscosity hybrid electroactive nanofluids (HENFs) demonstrated remarkable specific energy and power (305 F/g) even at low concentrations (0.025 wt%). Moreover, magnetic nanofluids serve as a versatile platform for catalysis due to their high surface-area-to-volume ratio and facile separability. By immobilizing catalytic nanoparticles onto magnetic supports, recyclable catalysts with enhanced activity and selectivity are achieved. Furthermore, functionalized magnetic nanofluids featuring catalytic nanoparticles contribute to environmental purification by facilitating the degradation of pollutants, particularly in water treatment applications targeting contaminants such as heavy metals, dyes, and organic pollutants [62]. Innovative research endeavors have explored novel applications of magnetic nanofluids, such as the investigation conducted by Li et al. [63] on the photothermal evaporation of magnetic nanofluids under a magnetic field, and the utilization of Ag nanofluids as a working fluid for solar evaporation by Parsa et al. [64], which also extends to desalination and water disinfection.

5. Challenges and Prospects of Magnetic Nanofluids

5.1. Challenges of Magnetic Nanofluids from Preparation to Application

Magnetic nanofluids boast extensive potential in advancing heat transfer applications. Some investigations into flow heat transfer, such as the augmentation of thermal conductivity via magnetic nanofluids under external magnetic fields, have been explored [65]. Notably, the magnetic manipulation of liquid flow enables the creation of innovative channel geometries and facilitates cargo transportation under low pressures, surpassing conventional methodologies. This breakthrough opens new avenues in the realm of microfluidics, promising advancements in low shear flow and pumping—a necessity in thermal management, fluid mechanics, and micro- and nanodevices. However, systematic studies on the preparation of magnetic nanoparticles, the magnetohydrodynamic thermophysical characteristics of nanofluids, and the utilization of microfluidic heat exchange remain scarce. Particularly, the absence of prediction models for the thermophysical properties of magnetic nanofluids poses a significant challenge.

5.2. Prospects of Mass Transport and Energy Conversion via Magnetic Nanofluids

The transformative potential of magnetic nanofluids in reshaping mass transport and energy conversion processes is unparalleled, offering a unique synergy of heightened thermal conductivity and magnetically regulated fluid dynamics that lays the groundwork for efficient energy systems and advanced manufacturing techniques. Their capacity to finely manipulate flow dynamics under magnetic influence unlocks opportunities for more effective cooling systems, targeted drug delivery mechanisms, and innovative approaches to energy generation and storage. Particularly noteworthy is their utility in microfluidic devices, facilitating the construction of intricate fluidic channels essential for the operation of lab-on-a-chip systems and other compact analytical instruments. This breakthrough holds promise for the development of smaller, yet more powerful, devices for chemical analysis, environmental monitoring, and medical diagnostics. Moreover, the enhanced thermal properties of magnetic nanofluids find ideal applications in solar thermal collectors, waste heat recovery units, and thermal energy storage systems, thereby augmenting thermal conductivity and heat transfer efficiency [66–68]. The dynamic manipulation of these fluids' thermal characteristics through magnetic fields adds an extra dimension of adaptability, optimizing energy capture, storage, and conversion processes to meet evolving conditions or operational demands.

Unlocking the full potential of magnetic nanofluids in these domains necessitates tackling several hurdles. These include the fabrication of stable and high-performance magnetic nanofluids via customized nanoparticle synthesis, the development of sophisticated computational models for precise behavior forecasting, the establishment of cost-effective and scalable manufacturing methods for widespread commercialization, and thorough environmental and safety evaluations to ensure sustainable utilization. Surmounting these obstacles will unleash the extraordinary capabilities of magnetic nanofluids, ushering in a new era of innovation in fluid dynamics and energy technology, thereby substantially propelling technological advancement and industrial progress.

5.3. Additional Remarks for Future Work

At present, there are still many challenges in the research and application of magnetic nanofluids (Figure 11). Mixed nanofluids refer to composite nanofluids formed by two or more different types of nanoparticles suspended in the base fluid [69]. These different types of nanoparticles can have different physical, chemical, or functional properties, and their combination can give mixed nanofluids more performance and application characteristics. Numerous researchers have discovered that the enhancement of thermophysical performance in mixed nanofluids rivals that of convective thermal conductivity. This suggests the potential application of magnetic fields in mixed nanofluids, which could influence both convective thermal conductivity and system voltage drop. Moreover, the presence of a magnetic field affects the thermal conductivity coefficient in magnetic nanofluid applications. As the magnetic field intensity and nanofluid concentration increase, so does the convective thermal conductivity of mixed nanofluids. Hence, it is imperative to consolidate the characteristics of mixed nanofluids with these various attributes. Furthermore, nanofluids should be employed in diverse heat regimes to investigate changes in heat properties and the features of such regimes using nanofluids.

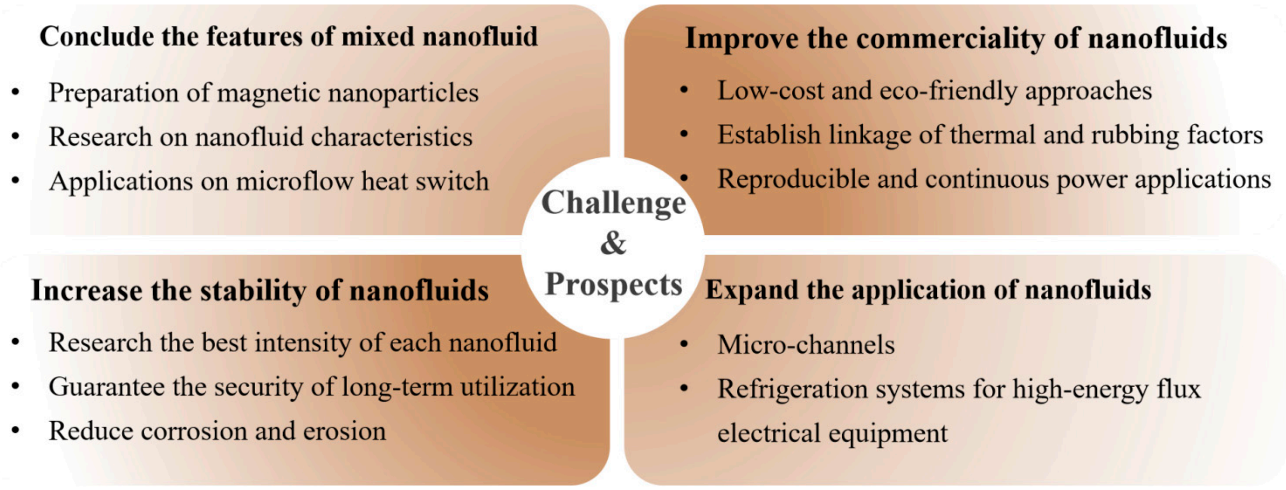

Figure 11. Challenges and prospects of magnetic nanofluid.

The impact of nanofluids on the stability of convective thermal conductivity in heat power systems has been extensively studied, contributing to their valid utilization in high-flux project systems. The heat characteristics of nanofluids improve as the nanofluid density increases. However, as the dispersed stability of nanofluids decreases, nanoparticle agglomeration occurs, significantly reducing thermal conductivity and nanofluid uptake. Thus, it is crucial to research the optimal concentration of each nanofluid for utilization in heat regimes and to devise strategies to ensure long-term safety.

Additionally, other factors influencing the convective thermal conductivity of nanofluids, such as the hydrodynamic characteristics of nanoparticle liquid levels and nanofluid, warrant deeper investigation beyond the enhancement of heat transfer due to intensified Brownian movement. Furthermore, issues related to the long-term utilization of nanoparticles in heat regimes, including corrosion and erosion of thermal conduction interfaces, must be addressed. Attention should also be directed towards the use of nanofluids in microchannels or refrigeration systems for high-energy flux electrical equipment. One of the primary challenges is the relatively high cost of manufacturing nanofluids for industrial-scale operations. To expand the utilization of nanofluids in other industrial operations, it is imperative to establish innovative, low-cost, and eco-friendly approaches. Additionally, a universal framework of thermal and frictional factors applicable to various pipe shapes and nanoparticles, as well as nanofluids, needs to be developed for reproducible and continuous power applications.

6. Conclusions

This article provides an overall conclusion of burgeoning magnetic nanofluids, embracing their innovative designs and diverse uses. We have discussed the applications of magnetic nanofluids in forming micro- and mini-particle organization, including their magnetic responding features; we have also highlighted the endeavors in exploiting magnetically motivated soft materials and concluded with the self-assembly of iron-magnetic particles from their photonic constructions. Next, the discussion extended to their incorporation with tailored surface and microfluidic systems, exhibiting benefits in fluid and droplet manipulation. This paper also discussed the usefulness of magnetic nanofluids in various power and project applications, such as heat transmission, power collection, and oil uptake. Yet, there are still a few critical problems that need to be resolved to enable the applicability as well as the usability of iron flows. Firstly, the basic study of iron flows is still somewhat inadequate. Up until now, the influences of iron magnetic particle scale, particle concentration, and magnet strength on magnetic nanofluids characteristics have been the subject of extensive research, but little is understood regarding the influences of particle construction, forms, and element contents on magnetic nanofluids' features such as magnetic strength, hydrodynamics, and magneto-heat functions. Furthermore, more improvement and refinement of the manufacturing techniques of iron-magnetic particles are still required. The manufacturing of well-distributed iron magnetic particles remains to be pursued; in the same way, the mass production of complex structured and superficially functionalized particles and particles that were doped with other factors is under constant development and exploration. Moreover, since the exact operation of the magnetic field on magnetic nanofluids is confined to a small area, a larger scale of accurate operation of magnetic nanofluids is needed.

The majority of the subsequent research can be concentrated on the uses of magnetic nanofluids in other areas of advancement, which consist of smart devices, harvesters of solar radiation, and soft devices, and their combined use with other platforms. It is possible to construct a multi-modal and multi-pathway medical diagnosis and therapy platform by connecting iron-magnetic particles with other functional nanomaterials. Furthermore, these findings can be applied to daily life and medical fields. To realize this purpose, upgrading and refinement are needed to simplify the operation procedures, enhance the modularization of the system module, and achieve functional optimization. In conclusion, additional research on the characteristics of magnetic nanofluids will lead to improvements in manufacturing technology, functional platforms, and relevant scientific discoveries. We are convinced that magnetic nanofluids can inspire scientists from different disciplines to continue their research and achieve breakthrough goals.

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Conflicts of Interest: The authors declare no conflict of interest.

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