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Magnetohydrodynamics of nanofluid internal forced convection: A review and outlook for practical applications

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ABSTRACT

Nanofluids (NFs) have emerged as a revolutionary medium for enhancing heat transfer, with magnetohydrodynamics (MHD) gaining particular attention for its potential to improve system efficiency. Despite this growing interest, a critical gap remains in understanding the combined impact of Fe_3O_4 and its hybrid nanofluids under magnetic fields, especially in turbulent and transition flow regimes of internal forced convection. This review offers an in-depth exploration of MHD-NF internal forced convection, addressing key aspects such as magnetic field dynamics, nanoparticle clustering, stability, dispersion, flow control, and responsive rheology. Leveraging a comprehensive bibliographic analysis of 100 experimental studies from 2010 to the 2024, along with data from the Scopus® database, this work highlights how optimized nanofluid volume concentrations, magnetic field intensities, and frequencies significantly enhance heat transfer coefficients. The findings underscore that both magnetic field strength and nanoparticle concentration critically influence particle motion, flow patterns, entropy generation, thermal performance, and pressure drops, offering new insights into system design. The versatility of MHD-NF systems presents promising applications in fields ranging from advanced cooling technologies to solar thermal systems and material processing. Furthermore, this review addresses ongoing debates on the efficacy of alternating versus constant magnetic fields, advocating for customized magnetic field configurations to unlock the full potential of MHD-enhanced heat transfer. This work not only identifies existing gaps but also lays the foundation for future breakthroughs in magnetically influenced nanofluid systems.

Introduction

Efficient heat transfer lies at the heart of countless innovations in science and engineering, shaping advancements across a myriad of industries. Recent strides in this pursuit have been marked by introducing nanofluids, a ground-breaking concept introduced by Choi, where nanoparticles are seamlessly blended into conventional fluids. This ingenious amalgamation has captivated researchers and engineers alike, offering the promise of significantly enhancing thermal management in different systems [1]. Several studies have shown that they can be utilized for either active or passive cooling systems depending on application [2–4].

Nanofluids, with their unique thermal properties, have emerged as a versatile tool for optimizing heat transfer across a diverse range of applications. From the demanding realm of electronics cooling, where the relentless quest for efficient heat dissipation reigns supreme, to the dynamic landscape of energy generation, nanofluids have demonstrated their potential to enhance thermal efficiency with remarkable efficacy [5,6]. In recent times, nanofluids have been utilized as a highly effective coolant in industries such as automotive [7], HVAC systems [8], heat exchangers [9], solar thermal systems [10], biomedical devices [11], electronics cooling [12], nuclear reactors [13], energy efficiency, and material processing [14]. The incorporation of nanofluids in these systems has led to improved heat transfer efficiency, better performance, and energy savings.

Sundar et al. [17] examined nanodiamond-Fe_3O_4 hybrid nanofluids in circular tubes with twisted tape inserts, observing significant enhancements in Nusselt number and exergy efficiency. With a twist ratio

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of 5, heat transfer improvements reached 73.04 %, while the thermal performance factor (TPF) peaked at 1.545, demonstrating the synergistic effect of nanofluids and enhanced flow techniques in turbulent regimes. Adogbeji et al. (2024) studied Fe_3O_4/TiO_2 hybrid nanofluids in turbulent flow, identifying 0.0125 % vol as the optimal concentration for maximizing convective heat transfer (26.33 % improvement) while maintaining stability and minimizing pressure drop. Stability tests showed better nanoparticle dispersion at lower concentrations (0.00625 %–0.025 % vol), whereas higher concentrations led to sedimentation and increased viscosity, raising pressure losses. The study highlights the need to balance heat transfer enhancement with energy efficiency by optimizing nanoparticle concentration. These experimental studies among others like Sundar et al. [18], Colla et al. [19] and, Zamzamian et al. [20] have proved the superiority of nanofluids to conventional fluids for improved thermal performance in forced convective flow in tubes or pipes.

Ibrahim et al. [15] explored the impact of nanoparticle size on forced convective heat transfer characteristics of Al_2O_3-MWCNT hybrid nanofluids in the transitional flow regime. Their findings revealed that Al_2O_3 (20 nm) – MWCNT (<7 nm) combination achieved the highest heat transfer performance, with a 48.86 % increase in the Nusselt number, while also exhibiting the lowest friction factor and pressure drop. These results underscore the influence of nanoparticle size on thermal efficiency, pressure drop, and critical Reynolds number, affecting the onset and conclusion of the transition regime. In another study, Ibrahim et al. [16] investigated mixed convection heat transfer in thermally developing flows using Al_2O_3-MWCNT hybrid nanofluids. The effects of the percentage weight composition (PWC) of nanoparticles were assessed across different flow regimes. Al_2O_3 (60 %)–MWCNT (40 %) yielded the highest heat transfer enhancement, especially in the laminar regime, demonstrating the critical role of PWC in modulating flow characteristics and enhancing heat transfer.

Nevertheless, the advantage of nanofluids transcends their improved thermophysical properties and magnetic behavior. The interaction of magnetic fields with nanofluids in conduits like pipes has added a fascinating aspect to their behavior. This unique interplay between magnets and fluid flow creates an intriguing field known as magnetohydrodynamics (MHD). Magnetohydrodynamics (MHD) of nanofluids in pipes investigates how magnetic fields influence nanofluid behavior within confined conduits [21–23]. It is a significant field due to its potential to enhance heat exchange across various domains. MHD's focal point lies in understanding the complex interactions between nanofluids, pipes, and magnetic fields, revealing their combined effects on fluid flow, heat transfer, and other properties [24–26].

Magnetohydrodynamics of nanofluids in pipes has practical applications in advanced electronics cooling technology and optimizing heat transfer efficiency, while magnetic fields are deftly employed to manipulate fluid flow, ensuring precision cooling in the face of mounting thermal challenges [5]. Within this domain, we explore how magnetic fields interplay with nanofluid used in forced convection heat transfer, giving rise to intricate dynamics that transcend conventional heat transfer paradigms [27,28]. A typical schematic of magnetohydrodynamics of nanofluids forced convection is explained in Fig. 1. The role of magnetohydrodynamics in augmenting forced convection heat transfer and the behavior of nanofluids under the magnetic influence is highly significant [29]. This is due to the flexibility of manipulating the fluid behavior with varied magnetic field properties.

The interaction between magnetic flux and nanofluids can alter fluid flow dynamics, impacting thermal energy transfer characteristics. Understanding magnetohydrodynamics in nanofluids is crucial for optimizing thermal performance in practical applications, as shown in Fig. 2, where the ideal combination of methodologies is essential. Investigating magnetohydrodynamics in nanofluids within pipes employs various numerical and experimental methods, examining laminar and turbulent flows of single and hybrid nanofluids.

Numerical studies have extensively advanced the understanding of magnetohydrodynamic nanofluid convection, offering valuable insights into its behavior under complex conditions and geometries. However, detailed experimental investigations in this field remain relatively limited. Mousavi et al. (2016) analysed a sinusoidal double-pipe heat exchanger numerically using Fe_3O_4 nanofluids, demonstrating that magnetic fields and tube geometry significantly enhance heat transfer by promoting fluid mixing. Biswas et al. (2021) demonstrated that oblique-wavy porous enclosures filled with Cu–Al_2O_3–H_2O hybrid nanofluid achieve a 22.16 % heat transfer enhancement with wavy walls, while partially active magnetic fields centrally positioned offer thermal control despite a 13.97 % reduction in heat transfer. Mandal et al. (2022) explored Cu-water nano liquids in partially driven cavities, showing up to an 88.39 % heat transfer improvement with higher Reynolds and Richardson numbers, emphasizing the role of flow dynamics and cavity orientation. Their subsequent study on W-shaped porous cavities revealed a 56.48 % heat transfer boost through geometric optimization, though performance decreases with stronger magnetic fields.

Gerdroodbary et al. (2023) analyzed ferrofluid flow in screw heat exchangers under non-uniform Kelvin forces, finding that the Reynolds number had a stronger influence on flow behavior than screw diameter.

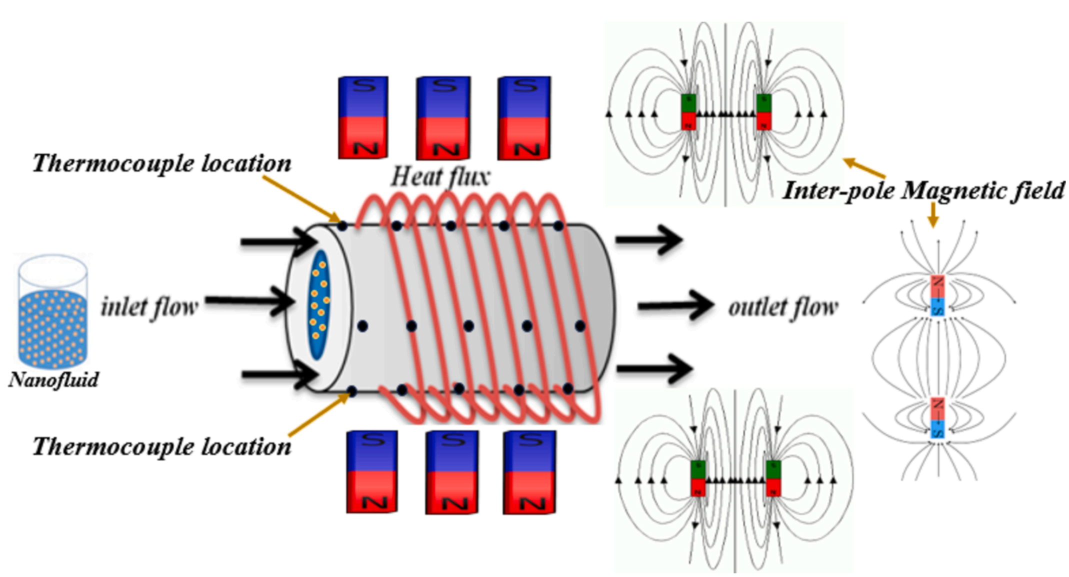

Fig. 1. Schematic Diagram of a Typical Magnetohydrodynamics of Nanofluids Forced Convection.

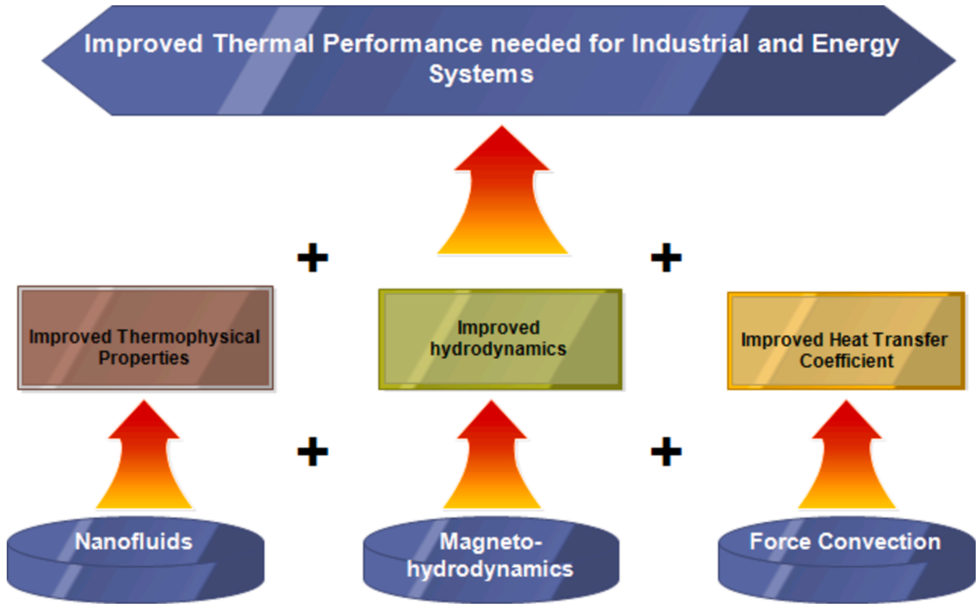

Fig. 2. Relevance of MHD Nanofluids Forced Convection to Heat Transfer.

However, increased screw diameter significantly raised skin friction. This study highlighted the synergy between magnetic fields, geometry, and flow parameters in optimizing thermal performance, supported by experimental validation. Earlier, Gerdroodbary (2019) applied a GMDH neural network to predict heat transfer rates in MHD nanofluid flows within inclined sinusoidal enclosures. The results demonstrated that the GMDH model surpassed conventional methods in accuracy, with buoyancy, nanoparticle concentration, and enclosure slope being critical parameters, while higher Hartmann numbers diminished heat transfer efficiency. Halder et al. (2024) highlighted that Co-kerosene nanofluid in butterfly-shaped cavities achieves a remarkable 101 % heat transfer enhancement through optimized wing angles and reduced magnetic intensity while minimizing entropy generation. Collectively, these findings highlight the potential of magnetohydrodynamic techniques, supported by computational and data-driven approaches, to optimize heat transfer in thermally demanding applications by leveraging fluid properties, magnetic fields, geometric configurations, and precise modeling for enhanced performance.

Zhang and Zhang (2021) investigated magnetic nanofluids under alternating magnetic fields and found that heat transfer performance improved with increasing frequency and volume fraction, especially at low Reynolds numbers. Similarly, Mohammadfam et al. (2023) assessed the effects of Fe_3O_4, Fe_3O_4-MWCNT, and Fe_3O_4/MWCNT nanofluids under magnetic fields, highlighting significant improvements in thermal conductivity and convective heat transfer coefficient (CHTC). Their results showed that Fe_3O_4@MWCNT nanofluids, at a concentration of 0.2 wt%, achieved a 5.94 % increase in thermal conductivity and a 50 % improvement in CHTC at Reynolds number 2200. Notably, the application of magnetic fields enhanced CHTC for Fe_3O_4-based nanofluids but led to a reduction for Fe_3O_4/MWCNT nanofluids at higher concentrations.

Adogbeji et al. (2024) [30,31] explored the effects of magnetic fields and waveforms on heat transfer, thermal efficiency, and pressure drop in Fe_3O_4/TiO_2 nanofluids within a heated copper tube. Optimal conditions (4 V, 60 Hz) improved heat transfer, while higher frequencies and voltages reduced efficiency due to stronger magnetic fields. Waveform types (sine, square, triangular) influenced nanoparticle alignment, turbulence, and flow resistance. Lower nanoparticle concentrations (0.00625 %–0.1 %) enhanced heat transfer through improved dispersion, achieving up to 28.21 % enhancement with a square waveform, compared to 16.5 % without a magnetic field. The study underscores the importance of magnetic fields and nanoparticle optimization for enhancing thermal system performance, aligning with findings in related research. In another study, Adogbeji et al. (2024) [32] examined Fe_3O_4/-MgO/DIW magnetic hybrid nanofluids (MHNFs) across different flow regimes, finding delayed transition onset at higher Reynolds numbers due to enhanced viscosity and thermal conductivity. A 31.6 % heat transfer enhancement was achieved at 0.0125 % vol in the transition regime, with lower concentrations (0.00625 %–0.0125 % vol) providing optimal performance. Higher concentrations increased pressure drop, emphasizing a trade-off between heat transfer and flow resistance. The Total Efficiency Index (TEI) confirmed 0.0125 % vol as the ideal balance for thermal efficiency. MHNFs demonstrated potential for high-performance cooling and thermal management applications, with future research needed to improve stability and reduce viscosity-related challenges.

Traditional heat transfer fluids often struggle to meet the increasing thermal demands of advanced technologies. While nanofluids (NFs) have shown promise in enhancing heat transfer performance, their full potential under the influence of magnetic fields known as magnetohydrodynamics (MHD) remains underexplored, particularly in turbulent and transitional flow regimes in internal forced convection. By combining MHD with nanofluids, researchers can manipulate particle dispersion and flow characteristics, enabling significant improvements in heat transfer efficiency. This integration is particularly beneficial for applications requiring precise thermal management, such as electronics cooling, solar power systems, and industrial heat exchangers. However, despite the promise of these systems, a critical gap persists in understanding the effects of magnetic field modulation and nanoparticle concentration on performance, especially in turbulent flows. Addressing these gaps involves investigating the various factors summarized in Fig. 3, where magnetic effects, nanofluid properties, and forced convection dynamics have been systematically categorized. By optimizing these parameters, future research can advance the development of high-performance cooling systems while tackling challenges such as stability and viscosity in magnetohydrodynamic nanofluids.

This review provides an in-depth exploration of magnetohydrodynamic nanofluid (MHD-NF) internal forced convection, a promising approach to enhancing heat transfer performance in advanced thermal systems. Key aspects such as magnetic field dynamics, nanoparticle clustering, stability, dispersion, flow control, and responsive rheology are examined to highlight how magnetic forces influence fluid behavior

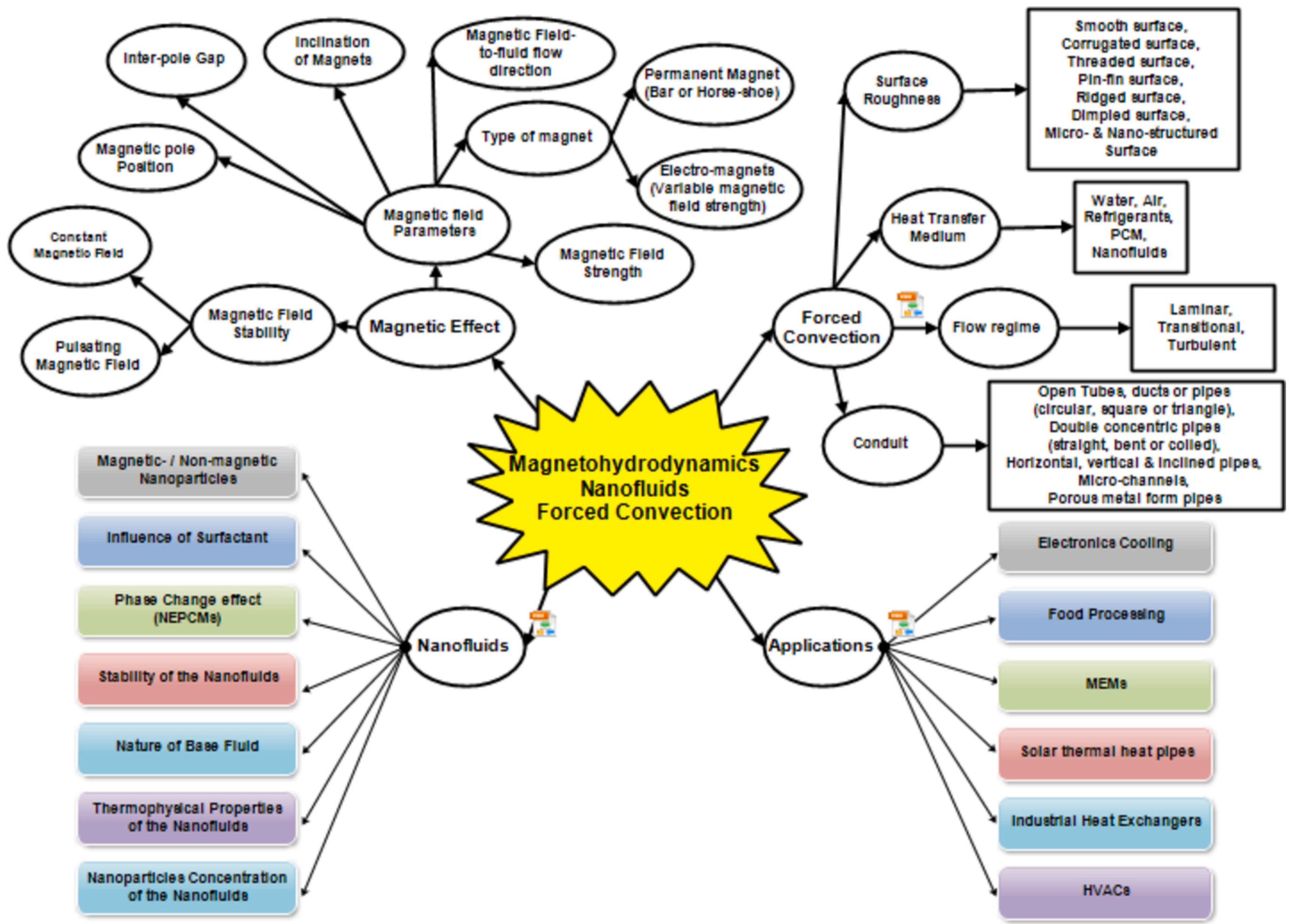

Fig. 3. Mind-map on MHD Nanofluids Forced Convection.

at both micro and macro scales. This work addresses ongoing debates on the efficacy of alternating versus constant magnetic fields, emphasizing their impact on flow modulation and thermal performance. Alternating magnetic fields offer dynamic control over nanoparticle movement and heat transfer enhancement, while constant fields provide steady-state benefits in specific applications. By analyzing these effects, this review aims to bridge knowledge gaps and guide the design of optimized MHD-NF systems for practical applications in cooling technologies, energy systems, and industrial processes.

Materials and methods

Magnetohydrodynamics (MHD) principles and effects on nanofluids

According to Hussain et al. [33], the basic principles of magnetohydrodynamics (MHD) are typically associated with electrically conducting fluids such as ionizing gases, plasmas, and metals, but these principles also extend to nanofluids containing conducting nanoparticles, creating distinct interactions when exposed to magnetic fields. Nanofluids' electrical conductivity is greatly influenced by the choice of nanoparticles, particularly metallic ones such as copper (Cu), silver (Ag), gold (Au), aluminum (Al), nickel (Ni), iron (Fe), platinum (Pt), titanium (Ti), and carbon nanotubes (CNTs). These nanoparticles are known for their excellent heat-conducting properties and large surface areas, making them valuable additions to nanofluids, nanocomposites, and thermal interface materials. When subjected to magnetic fields, nanofluids with these metallic nanoparticles exhibit unique behaviors due to their electrical conductivity. These properties find applications in electronics cooling, heat exchangers, thermal management systems, and nanoscale heat dissipation solutions, leading to enhanced efficiency and performance in various industries.

General effects and phenomena of MHD in nanofluids

MHD in nanofluids can lead to various key effects and phenomena that impact the behavior of these fluids. Some of the significant effects and phenomena of MHD-NF include magnetic-induced motion and clustering, stability control and dispersion, nanofluid flow control, enhanced mass transfer, and responsive rheology. These phenomena are further explained in the following subsections.

Magnetic field-induced nanoparticle motion and clustering

When a nanofluid encounters a magnetic field, the magnetic forces influence the nanoparticles within the fluid, potentially leading to their movement, rearrangement and sometimes clustering. The nanoparticle motion depends on the magnetic field's intensity and alignment [34]. Magnetic field-induced nanoparticle motion and clustering occurs when nanoparticles in a nanofluid respond to an applied magnetic field.

Fundamental factors influencing this phenomenon are magnetic field strength, magnetic dipole–dipole interactions, and nanoparticle characteristics (particle size and magnetic characteristics) [35–37]. Notably, this phenomenon if adequately controlled, enables tailored nanofluid motion and clustering patterns, which is valuable in applications like gradient materials and magnetic field sensors, where changes in the external magnetic field influence nanoparticle alignment, allowing their use in sensing [38,39].

Magnetic field-induced stability control and dispersion

Magnetic fields are employed to control nanoparticle dispersion and stability in nanofluids, ensuring consistent performance and extending shelf life in applications like thermal management and electronic cooling [40,41].

Magnetic fields are essential for controlling nanoparticle dispersion and stability within nanofluids, ensuring long-term maintenance of desired properties and has significant implications for nanofluid technology [42]. In nanofluid technology, Stability Control utilizes magnetic fields to sustain uniform nanoparticle distribution and prevent agglomeration, ensuring long-term performance across various applications [41]. Moreover, this control mechanism extends the shelf life of nanofluids, allowing for prolonged storage without significant property degradation [43]. Furthermore, Magnetic field-based stability control facilitates precise customization of nanofluid properties, enhancing their versatility and reliability in applications such as thermal management, electronics cooling, and materials processing. This adaptability enables tailored solutions for various engineering challenges [44].

Magnetic field-induced flow control

Magnetic fields offer precise control over nanofluid flow in microfluidic devices and lab-on-a-chip systems, benefiting biotechnology and materials science applications. Magnetic field-based flow control enhances heat transfer, especially in microfluidic devices, by directing nanoparticle movement. This controlled motion improves convection currents, leading to more efficient heat distribution and transfer [45]. In microfluidic heat exchangers, precise convection control ensures even heat distribution and optimized thermal performance [46].

Magnetic fields can reduce heat boundary regions near solid surfaces, increasing heat transfer rates at the boundaries, which is crucial for electronic device cooling. In heat transfer, MHD-based flow control offers precise thermal conductivity regulation. Engineers can dynamically adjust thermal conductivity through magnetic field manipulation, benefiting applications like heat exchangers and energy generation systems [47,48].

Magnetic field-induced enhanced mass transfer

According to Felicia et al. [34], MHD in nanofluids presents an innovative approach to energy harvesting. It capitalizes on the controlled movement of nanoparticles within nanofluids under the influence of magnetic fields to generate electrical power. This concept is highly relevant to microscale applications such as microelectromechanical systems (MEMS) and wireless sensor networks. A key advantage is its scalability, making it suitable for powering small-scale devices and sensors. This has significant potential in various domains, particularly for sustaining operations in remote or challenging environments, where conventional power sources are impractical. A dependable and renewable energy source can be harnessed by continuously moving nanoparticles within nanofluids in ambient magnetic fields. Additionally, this concept has applications in energy-efficient microfluidic systems [49]. Its scalability, suitability for challenging environments, and potential for energy-efficient microfluidic systems make it a compelling area of research with broad implications for self-powered and autonomous technologies.

Magnetic field-responsive rheology

Utilizing magnetic nanoparticles (MNPs) and magnetic fields can significantly alter the rheological behaviour of nanofluids, which is especially beneficial in applications requiring precise flow control, notably microfluidic systems [50,51]. This phenomenon enables the fine-tuning of viscosity and flow properties, enhancing fluidic control in diagnostics, drug delivery, and lab-on-a-chip technologies [52]. It also extends to processes like inkjet and 3D printing and pharmaceutical drug formulation, improving process stability, product quality, and manufacturing efficiency [53]. The ability to tailor rheological properties in response to magnetic fields represents a versatile tool with vast potential across various engineering and scientific disciplines.

Magnetic field-induced alignment of nanoparticles and impact on physical properties

Magnetic alignment or chaining is a notable effect in which nanoparticles align along field lines, forming linear chains or aggregates, depending on field strength and nanoparticle concentration. This phenomenon has implications for the mechanical and thermal behavior of the nanoparticles, as it can be controlled. Magnetic field-induced alignment of nanoparticles enhances heat transfer in medical and engineering applications like drug transport systems, MRI contrast media cancer treatment, and energy-efficient cooling.

Basic principle of magnetic field-induced alignment. External magnetic fields can induce alignment or reorientation of magnetic nanoparticles in nanofluids, significantly impacting the fluid's behavior. Magnetic dipoles in the nanoparticles tend to align with the field's direction, creating magnetic alignment. This phenomenon arises from the interplay between the external magnetic field and the nanoparticles' intrinsic magnetic dipole moments. In response to the field, these nanoparticles, each with its own magnetic orientation, align themselves along the field lines. This collective alignment imparts unique properties to nanofluids, including enhanced thermal conductivity, controlled motion, and the formation of clusters. These effects find applications in heat transfer enhancement and sensing technology [54].

Alignment mechanism. Magnetic field-induced alignment in nanofluids occurs due to the torque exerted on each nanoparticle, causing their magnetic orientations to align along the field lines. This mechanism, driven by the rotational force or torque applied to individual nanoparticles, results in the collective alignment of particles along the magnetic field's axis. These regions of nanoparticle alignment are essential for various applications, including improving thermal conductivity, enabling controlled motion, and developing gradient materials. Understanding this torque-driven alignment is crucial for harnessing nanofluid properties in various technological domains [38,39].

Enhanced anisotropy. Magnetic nanoparticle alignment induces anisotropy in the nanofluid's properties. Anisotropy means that certain properties, such as thermal conductivity or electrical conductivity, become direction dependent [55,56]. This leads to significant property enhancements along the alignment direction, particularly notable in heat conduction. When magnetic nanoparticles align in response to external magnetic fields, the nanofluid displays anisotropic behaviour, where properties like electrical and heat conductivity become directionally sensitive. This results to pronounced variations based on orientation relative to the alignment direction. For instance, thermal conductivity can substantially increase along the magnetic field lines, offering considerable benefits in applications demanding efficient heat transfer, such as electronic device cooling and microchannel heat exchangers. Leveraging anisotropy through magnetic nanoparticle alignment enables tailoring nanofluid characteristics for specific engineering needs, driving advancements in heat transfer and materials science [57,58].

Magneto-optical effects. Magnetic alignment in nanofluids doesn't only impact thermal and electrical properties but can also induce magneto-optical effects, altering how the fluid interacts with light. This presents opportunities for applications in sensors and optical devices. The alignment influences the nanofluid's optical characteristics under the magnetic field, leading to changes in absorption, scattering, and refractive index. Such magneto-optical effects are promising for developing high-sensitivity magnetic field sensors and optical devices like advanced displays and tuneable lenses. Research in this field holds the potential to drive innovative technologies [59,60].

Magnetic field-induced viscosity changes. Magnetorheological fluids (MRFs) redefine heat transfer in tubes, offering dynamic and controllable solutions. Their ability to tune viscosity using magnetic fields enhances thermal efficiency and precise temperature control. This tunability benefits various applications requiring precise control over flow rates and shear forces [61–63]. MRFs transform heat transfer by enabling fine adjustment of fluid viscosity through magnetic field manipulation. This control significantly impacts heat transfer efficiency, permitting viscosity increase for better thermal contact and heat transfer, or reduction to lower pumping power needs, ultimately enhancing energy efficiency [64]. MRFs are versatile, applicable in scenarios from automotive cooling systems to microfluidic devices [61,65].

Magnetic field-induced pressure drops in MHD nanofluids. In systems employing MHD with nanofluids, the applied magnetic field strength and nanoparticle concentration are pivotal factors that influence pressure drop. Strong magnetic fields can induce significant particle motion and changes in flow patterns, contributing to higher pressure drops [66,67]. Increasing nanoparticle concentration raises nanofluid viscosity, adding to flow resistance and resulting in elevated pressure drops. Additionally, flow velocity and system design play essential roles in pressure drop management. Engineers and researchers must optimize these parameters to strike a balance between the benefits of enhanced heat transfer, courtesy of MHD in nanofluids, and the need to manage the increased pressure drop, ensuring efficient system operation without undue energy consumption or pressure loss.

Table

S/N	Effect/Phenomenon	Description	Applications/Implications	Ref
1	Magnetic field-induced motion and clustering	Magnetic forces cause nanoparticle movement, rearrangement, and clustering, influenced by field strength, dipole interactions, and particle characteristics.	Gradient materials, magnetic field sensors, and systems responsive to external field changes for tailored nanoparticle alignment.	[34–39]
2	Stability control and dispersion	Magnetic fields prevent nanoparticle agglomeration, ensuring uniform dispersion and long-term stability of nanofluids.	Thermal management, electronics cooling, and materials processing with extended shelf life and reliability.	[40–44]
3	Flow control	Magnetic fields direct nanofluid flow, enhancing convection and heat transfer, particularly in microfluidic systems and near solid boundaries.	Microfluidic heat exchangers, biotechnology, and energy systems requiring efficient heat distribution and precise thermal performance.	[45–48]
4	Enhanced mass transfer	Magnetic fields drive nanoparticle movement for energy harvesting and efficient microfluidic operations.	MEMS, wireless sensors, and systems for sustainable energy generation in remote or challenging environments.	[30,34,49]
5	Responsive rheology	Adjusting viscosity and flow properties of nanofluids using magnetic fields for better control.	Diagnostics, drug delivery, 3D printing, and pharmaceutical processes requiring precise fluidic behavior and stability.	[50–53]
6	Nanoparticle alignment and anisotropy	Magnetic fields align nanoparticles, inducing directional dependence in properties like thermal and electrical conductivity.	Heat transfer, sensing, energy-efficient cooling, and gradient materials with tailored anisotropic properties for advanced engineering solutions.	[38,39,55–57]
7	Magneto-optical effects	Changes in optical properties under magnetic fields, influencing light interaction with nanofluids.	High-sensitivity magnetic field sensors, tuneable lenses, and advanced optical devices.	[58,60]
8	Viscosity changes in magnetorheological fluids	Magnetic fields dynamically adjust nanofluid viscosity for improved thermal and energy efficiency.	Automotive cooling, microfluidics, and systems requiring tunable viscosity for optimized performance.	[61–65]
9	Pressure drops	Magnetic fields and nanoparticle concentration increase pressure drops, influenced by viscosity, flow patterns, and velocity.	Optimized system design balancing enhanced heat transfer with manageable energy consumption and pressure loss in industrial and engineering systems.	[66,67]

Mechanisms for enhanced heat transfer of MHD nanofluids force convection

Nanofluids, a ground-breaking development in thermal management, capitalize on the exceptional thermal conductivity of nanoparticles to enhance heat transfer. Magnetic fields enable precise control over the motion and alignment of these nanoparticles within the nanofluid, facilitating more efficient heat transfer through conduction, convection, and radiation processes. This effect finds applications in fields such as electronics cooling and magnetic fluid hyperthermia for cancer treatment, offering a promising approach to boost heat transfer efficiency. Magnetic field-induced motion of nanoparticles in nanofluids enhances thermal performance by improving the thermal boundary layer and reducing energy consumption.

Thermal boundary layer

Magnetohydrodynamics (MHD)-induced motion of magnetic nanoparticles within nanofluids significantly reduces the thermal boundary layer near solid–fluid interfaces, enhancing heat transfer rates in applications like electronic device cooling and microchannel heat exchangers. When exposed to an external magnetic field, these nanoparticles align and move, effectively thinning the thermal boundary layer. This effect contributes to energy efficiency across engineering systems, aiding in efficient heat dissipation and absorption [47]. However, research by Mahabaleshwar et al. [68] and Siddheshwar et al. [69] suggests that higher magnetic force intensity and lower surrounding medium permeability may reduce nanofluid flow and subsequently heat transfer performance.

Magnetic field-to-flow direction

This innovative enhancement in thermal conduction, driven by the motion and alignment of magnetic nanoparticles in response to magnetic fields, has diverse applications in heat transfer, such as in electronics cooling, energy systems, and targeted thermal management, offering precise control and improved heat transfer efficiency within nanofluids. Enhanced conduction in nanofluids capitalizes on nanoparticles serving as highly efficient thermal bridges between fluid layers, minimizing thermal resistance and creating pathways for efficient thermal energy redistribution within the fluid [70]. Control over nanoparticle motion via magnetic fields allows for precise tuning of thermal conduction.

Results from previous studies

Bibliometric analysis of recent MHD nanofluid forced convection studies

The progress of experimental studies on forced convection using conventional fluids (CF), nanofluids (NF), and MHD-NF in conduits was examined using data extracted from the **Scopus®** database. The result revealed that the field of forced convection using nanofluids (NF) and conventional fluids (CF) had significantly about 1460 and 4525 documents published, respectively. The bibliographic data in Fig. 4, shows the publication trend on forced convection using CF, NF, and MHD-NF in conduits (pipes, tubes, and ducts) in the last decade (2011–2024).

The data from Scopus also revealed that forced convective heat transfer in conduits was first studied using conventional fluids like water, air, and refrigerant since around 1909. The experimental forced convention studies using nanofluids commenced around 2004, and ever since then, there have been significant growth in the field of forced convention using nanofluids. Around 2011, studies on forced convection MHD-NF commenced, however with little publication count due to the difficulty and complexity of such studies. Up till date, only 141 publications are available in the field of forced convection using MHD-NF.

In Fig. 5, the keywords trend of research in this fields from the last decade are presented. Keen observation of this figure shows that words like; *CFD, FEM, peristaltic flow, entropy generation, magnetohydrodynamics, magnetite, electronic cooling, double-pipe heat exchanger,* among others are key words trending from publications in the last two years. Hence, forced convection MHD-NF has potential significance to industrial and energy systems because of its proposed enhanced thermal performance. This gap suggests a promising advancement for future research in MHD-NF within confined conduits and reaffirms the need for further exploration in this field.

Summary of previous published studies on MHD-NF

Zhang and Zhang [70] conducted experiments on magnetic nanofluids (MNFs) under the impart to alternating magnetic fields with varying frequencies (0–100 Hz), with Re of 944 to 8413, volumetric fractions of 1 % to 5 %, and magnetic flux strengths (0.01–0.09 T). Their results revealed that alternating magnetic flux improved local heat exchange coefficients, especially in the flow direction, with the rear of the flow channel experiencing more enhancement. Heat exchange was better with lower Re but less effective at higher ones. Heat exchange efficiency consistently improved with more nanoparticle volume fractions, regardless of magnetic fields. However, for volume fractions above 3 %, increasing field frequency had little impact on heat transfer. Higher volume fractions and frequencies increased pressure drops, and overall heat transfer improvement varied quadratically with frequency and Reynolds numbers. This improvement was attributed to magnetic nanoparticle movement and eddy motion within MNFs.

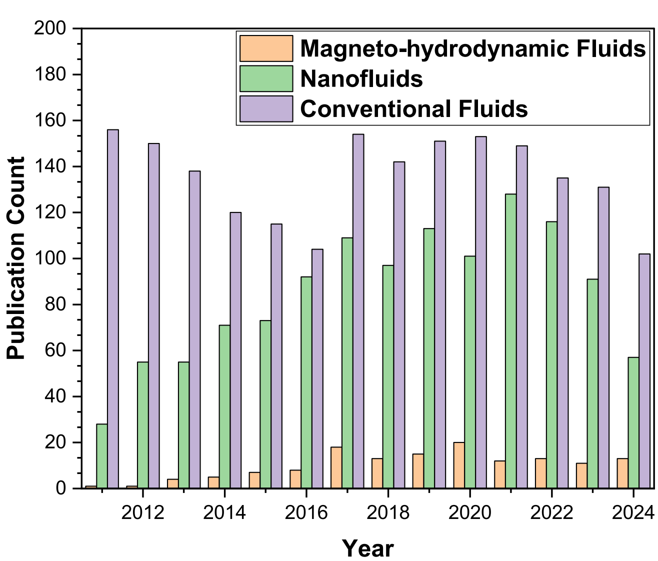

Fig. 4. Publication Trends on Forced Convection In Conduits using Nanofluids, MHD-Nanofluids and Conventional Fluid.

Ebaid et al. [71] study experimentally investigations to examine the impact of magnetic manipulation on enhancing heat exchange using Fe_3O_4/water in a heated tube and their experiments encompassed Reynolds numbers ranging from 2180 to 9160 and the concentration levels varying from 0.3 % to 1.2 %. They conducted their study both with and without the application of a magnetic flux. Their observations indicated, neglecting the magnetic flux effect, the Nusselt number (Nu) exhibited a 16.7 % increase with rising Reynolds numbers for the nanofluids compared to water. However, they also noted that the average heat exchange coefficient and Nu increased by 9.4 %, 26.1 %, 31.3 %, and 8.8 %, 13.1 %, and 23.9 % when exposed to the influence of the magnetic field (with field strengths of 15.5, 30.3, and 45.5 mT), in comparison to water devoid any magnetic flux effects. Additionally, their research reported that the pressure drop rises with Re and magnetic field intensity enhanced.

Lee et al. [26] examined the impact of a magnetic flux on forced convective heat exchange properties of various nanofluids, including, EG-based/Fe_3O_4 nanofluids, water and Fe_3O_4/MWCNT (Multi-Walled Carbon Nanotubes) hybrid nanofluids. The experiments covered a Re of 1000 to 1600 and a nanoparticle volumetric ratio spanning 0.025 % to 0.2 %. Their observations revealed the highest convective heat exchange efficiency of MWNCT nanofluids, with enhancements of 3.23 % and 2.78 % observed for MWNCT nanofluids containing 0.1 wt% Fe_3O_4 and 0.2 wt% Fe_3O_4, respectively. Furthermore, they observed an uptick in the typical pressure drop, with increments of 4.73 % and 5.23 % observed for nanofluids containing 0.2 wt% Fe_3O_4 and 0.2 wt% Fe_3O_4/MWNCT, respectively. Table 1 provides a comprehensive overview of prior experimental investigations into the MHD characteristics of magnetic nanofluids within pipes, including flow regimes, Reynolds numbers, nanofluid types, magnetic field characteristics, and heat transfer enhancement processes.

Tekir et al. [72] experimentally conducted a study to investigate how the existence of a constant magnetic field impacts the phenomenon of convective heat exchange of the Fe_3O_4/Cu/water and the experiments covered a Re spanning from 994 to 2337 and nanoparticle volume fractions ranging from 0.02 % to 2.0 %. They observed that the increased flow rate resulted in an increased Nu number and the Fe_3O_4 and Cu nanofluids increased convective heat exchange. In addition, the maximum convective heat exchange increased by 14 % when a magnetic flux was applied in contrast to no magnetic flux. Similarly, Table 2 summarizes research on the MHD behaviors of hybrid nanofluids in pipes subjected to magnetic fields, highlighting nanofluid composition and the magnetic field's effects.

There is a notable research gap in the field of magnetohydrodynamics (MHD) when it comes to the turbulent/transition regime. Current studies have primarily focused on laminar flows, and there is a dearth of literature that addresses the MHD behavior of hybrid magnetic nanofluids in internal forced convection under turbulent or transitional flow conditions. This is a critical area where further investigation and research are warranted to expand our understanding of how magnetic fields influence heat transfer and fluid flow in such conditions.

Application of MHD nanofluid forced convection

MHD nanofluids have been applied in several industries and energy systems. Some of these notable proposed application areas are discoursed further below. This proposed application area has shown MHD-NF forced convection to be the future of augmented heat transfer.

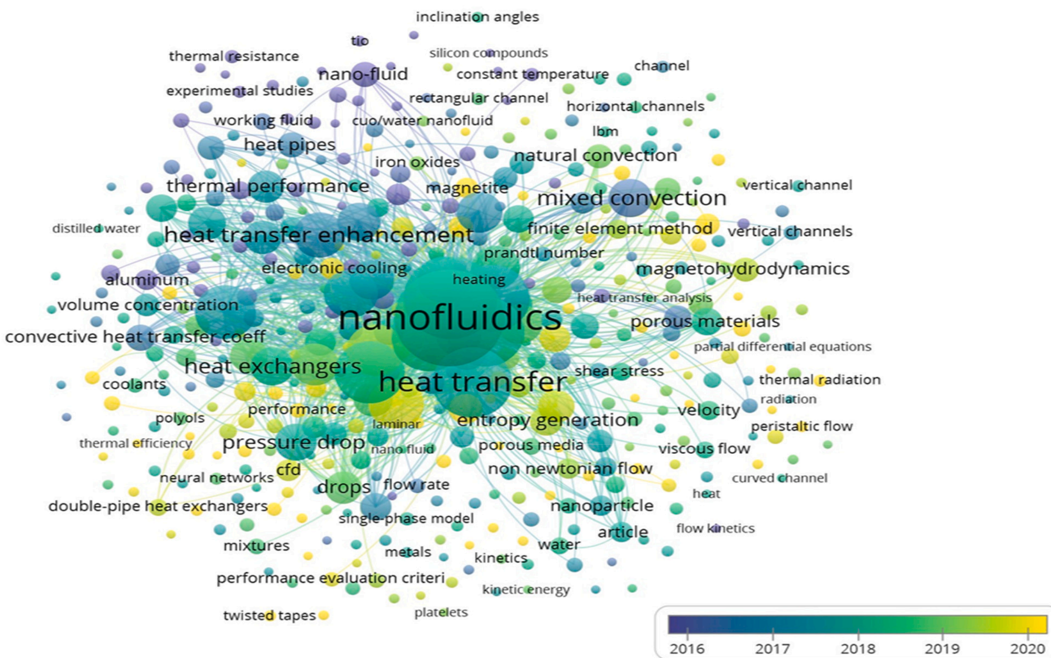

Fig. 5. Keywords trends in magnetohydrodynamics (MHD) with nanofluids.

Electronics cooling

Magnetohydrodynamics (MHD) nanofluids are instrumental in electronics cooling, efficiently dissipating heat from electronic devices like computer chips and high-performance processors. Through the incorporation of magnetic nanoparticles, these nanofluids enhance heat transfer by improving thermal conductivity and acting as efficient thermal bridges between fluid layers, reducing thermal resistance [95]. When exposed to an external magnetic field, these nanoparticles align and move, driving convective heat transfer and preventing overheating. This temperature regulation ensures stable operating conditions and prolongs the lifespan of electronic components, making MHD nanofluids indispensable for maintaining system reliability in high-performance electronic systems [96].

Building comfort in heating, ventilation, and air conditioning (HVAC) systems

MHD nanofluids are poised to revolutionize heating, ventilation, and air conditioning (HVAC) systems by enhancing heat transfer efficiency and temperature control while reducing energy consumption. These nanofluids optimize HVAC operations, ensuring quicker temperature adjustments and substantial cost savings. In air conditioning systems, they contribute to a more comfortable indoor environment with lower energy usage, making them a key technology for sustainable and energy-efficient building climate control solutions [97,98].

Automotive cooling

MHD nanofluids offer substantial potential for improving automotive engine cooling, enhancing engine efficiency, and reducing emissions in the automotive industry. Their excellent thermal conductivity enables efficient heat dissipation from critical engine components, contributing to lower operating temperatures and improved engine performance [99,100]. These nanofluids' thermal stability ensures consistent cooling performance under extreme conditions, aligning with the automotive industry's goal of higher efficiency and reduced environmental impact. MHD nanofluids are a promising technology for future automotive cooling systems [101,102].

Solar thermal systems

The utilization of MHD nanofluids in concentrated solar power (CSP) systems represents a significant advancement, greatly enhancing heat capture and transfer, and thereby increasing the overall efficiency of solar energy conversion. These nanofluids, known for their enhanced thermal conductivity, facilitate more efficient heat absorption and transfer within CSP systems, contributing to higher energy conversion efficiency. Their tuneable optical properties further enhance solar radiation absorption, leading to increased energy yield. Additionally, MHD nanofluids help maintain stable temperatures within CSP systems, preventing overheating and ensuring consistent energy output, thus promoting the adoption of sustainable and efficient solar thermal technology [96,103,104].

Nuclear reactors

The application of magnetohydrodynamic (MHD) nanofluids in nuclear reactors offers a transformative approach to enhance cooling efficiency and safety measures, critical for the optimal operation of nuclear facilities. These nanofluids, known for their high thermal conductivity, efficiently remove heat from reactor components, including the core and coolant loops, thereby improving overall cooling effectiveness and maintaining safe operating temperatures. Moreover, they enable precise temperature regulation within nuclear reactors, preventing overheating and ensuring stable thermal conditions, imperative for safe and efficient operations. Furthermore, MHD nanofluids exhibit radiation resistance, preserving their thermal properties even when subjected to ionizing radiation within nuclear reactors, thus safeguarding the integrity and longevity of cooling systems. This technology represents a significant advancement in nuclear reactor safety and performance optimization [105,106].

Materials processing

MHD nanofluids play a significant role in the field of materials processing, particularly in industries like metallurgy and materials science. These nanofluids provide several advantages for precise and efficient heat treatment and materials processing. With their enhanced

Table 1
Overview of Experimental works on MHD of Single Magnetic Nanofluids in Internal Forced Convection Flow pipes.

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Mechanisms to improve heat transfer
Yarahmadi et al. (2015) [67]	Fe_2O_4/H_2O	465 < Rec1160	Constant vertical non-homogeneous magnetic field (B < 0.07 T) and alternating vertical non-homogeneous magnetic field (B < 0.07 T; 10 Hz < f < 50 Hz)	Increase in particle volume concentration and magnet frequency. Maximum 19.8 % enhancement with Oscillating
Abadeh et al. (2015) [73]	Fe_2O_4/H_2O	0 < Re < 2500	Two stable and alternate magnetic fields of 1300 and 770 Gauss, employing four distinct styles of application.	Increase in particle volume concentration and magnetic field. Observations: Nu increased 11.85 % at 10 Hz and 14.8 % at 100 Hz. Frequency > 1000 Hz had no benefit.
Sun et al. (2020) [74]	Fe_3O_4/H_2O	400 < Re < 2000	Permanent magnet, 415, 700 gauss and 1.28 T, 40KHz	Increasing the magnet frequency and the alternating magnetic field. Maximum 32 % enhancement with 700 gauss with 28.6 gauss per millimeter magnetic field gradient.
Goharkhah et al. (2015) [75]	Fe_3O_4/H_2O	400 < Re < 2000		Augmentation of particle volume concentration, Reynolds number, and magnetic field intensity.
Zonouzi et al. (2017) [76]	Fe_3O_4/H_2O	580 < Re < 820	5x10x100mm of neodymium drupole magnet, 350mT	Introducing a magnetic field yielded substantial improvements: 23.4 %, 37.9 %, and 48.9 % higher particle concentration and enhanced local heat transfer coefficient.
Tekir et al. (2020) [72]	Fe_3O_4/H_2O	1122 to 2124	Constant/Alternative magnet,B = 0T,2T, 5 T and 15 Hz	Reducing Changes in magnetic field frequency yielded a 13 % boost in heat transfe
Goharkhah et al. (2016) [77]	Fe_3O_4/H_2O	200 to 1200	Constant vertical non-homogeneous magnetic field (0.03 T < B < 0.05 T), F = 5 Hz.,osillating vertical Constant vertical non-homogeneous magnetic field (0.03 T < B < 0.05 T) F5Hz	Higher particle concentration and magnet frequency raised laminar augmented convective heat transfer by 24.9 % and 37.3 % with constant and alternating magnetic fields, respectively, when contrasted with the absence of a magnetic field..
Mei et al. (2019) [78]	Fe_3O_4/H_2O	600 to 1100	Parallel magnetic induction intensity, B = OG, 100 G,200G,300G	Increase in particle density and magnetic field strength. They observed that the nanofluids with x = 5.0 % under magnetic induction intensity B = 300G showed the largest resistance coefficient.
Azizian et al. (2014) [79]	Fe_3O_4/H_2O	451 to 1061	permanent magnet, constant vertical non-uniform magnetic field (B < 0.02 T, F = 5 Hz.,50 Hz	At a Reynolds number of 745 and 32.5 mT/mm magnetic field strength, a notable pressure increase occurred. Adjusting to 430 mT with gradients of 8.6–32.5 mT/mm, the pressure rose by a maximum of 7.5 %.
Wang et al. (2019) [80]	Fe_3O_4/H_2O	0 to 1000	round hollow permanent magnet of inner dia of 39, outer dia of 62,10 mm thickness	Rising particle density and magnetic field intensity. Ferrofluids with a magnetic probe demonstrated enhancements in heat transfer of 26.5 % and 54.5 %.
Hatami et al. (2017) [27]	Fe_3O_4/H_2O	100 to 500	Electrically powered magnet, Steady vertical homogeneous magnetic field. (dH/dx < 9.6x10000000 A/m)	Heightened particle density and stronger magnetic field led to convective heat transfer improvement exceeding 60 % with magnetic nanoparticles.
Ashjaee at al. (2015) [81]	Fe_3O_4/H_2O	200 to 900	External Electromagnet, B < 1,400 G	Elevation in particle density and the field intensity. when a field of 1,200 Gauss was employed in the ferrofluid, it increased by 38 %.
Sadrhosseini et al. (2016) [82]		120 to 240	seven ferrite cores used for the magnetic field, 200 guess. Frequency of 7.81 Hz	A magnetic field improves thermal exchange, and porous media leads to uniform temperature distribution. Among these factors, nanoparticle volume percentage significantly impacts heat transfer.
Amani et al. (2017) [83]	Fe_3O_4/H_2O	100 to 1200	Constant magnet 200	Raising particle volume concentration and applying a 100 G (0.01 T) magnetic field significantly improved heat transfer, with a maximum enhancement of 5.9 % at 2 wt% and Reynolds number (Re) of 200. This improvement further rose to 8.5 % when the magnetic magnitude reached 200 G (0.02 T).
Ghofrani et al. (2013) [84]	Fe_3O_4/H_2O	80 to 1350	Eletromagnet, constant vertical non-uniform magnetic field and alternative magnet (B < 0.02 T), f = 5 Hz,50 Hz	Increasing particle density and magnetic field strength, they found that employing a 50 Hz alternating magnetic field improved convective heat transfer by 5 % compared to no magnetic field, while a constant magnetic field showed no improvement.
Lajvardi et al. (2010) [85]	Fe_3O_4/H_2O	0 to 265		Elevation in particle density and magnetic field intensity.
Sha et al. (2017) [86]	Fe_2O_4/H_2O	4000 to 6500	orthogonal, consistent, and varying magnetic field	Increase in particle volume fraction, thermal condition, and magnetic strength.
Guzei el al. (2017) [87]	Fe_2O_4/H_2O	00 to 2500	3 parmanent neodymum magnets, 0.3 T	The augmentation in both particle volume concentration and the utilization of a magnetic field caused a 35 % improvement in heat exchange effectiveness.
Ebaid et al. (2022) [71]	Fe_3O_4/H_2O	1000 to 6000	Field magnitude (F = 15:5, 30:3, 45:5) mT	Elevated Nusselt numbers with a magnetic field led to increased average heat exchange coefficients and Nu. The improvements were 9.4 %, 26.1 %, 31.3 %, and 8.8 %, 13.1 %, and 23.9 %, respectively.
Asker et al. (2016) [88]	Fe_3O_4/H_2O	2900 to 9160	constant magnetic field. magnetic intensity of (0.1, 0.2, 0.3 Tesla),	Increase in particle volume concentration and magnetic field. they gain increased to (43.9, 44.3, 46 %)

(*continued on next page*)

Table 1 (*continued*)

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Mechanisms to improve heat transfer
Zhang and Zhang (2021) [70]	Fe_3O_4/H_2O	944 to 8413	Different frequencies of alternating magnetic fields spanning from 0 to 100 Hz and magnetic field strengths spanning from 0.01 T to 0.09 T	An external alternating magnetic field enhanced heat exchange at lower Re but reduced it at higher Re. Higher nanoparticle concentration and magnetic field frequency increased pressure drop, but beyond 3 % volume fraction, the frequency had a limited impact on heat transfer. Overall, heat transfer improved within the 0–100 Hz range of alternating magnetic fields.

thermal conductivity, they ensure uniform and efficient heat distribution, thereby optimizing the quality of metallurgical and materials treatments. Additionally, they enable precise temperature control, critical in applications such as annealing and tempering, to achieve desired material properties. Moreover, by improving heat transfer efficiency, MHD nanofluids contribute to reduced energy consumption, resulting in cost savings and environmental benefits, making them a valuable tool in modern materials processing industries [107].

Biomedical devices

MHD nanofluids are essential in advancing hyperthermia machines and other biomedical devices for precise cancer cell targeting, a crucial aspect of cancer treatment, offering optimal therapeutic outcomes. These nanofluids enable meticulous temperature control, selectively heating cancer cells while safeguarding healthy tissue [108]. Moreover, they ensure uniform heat distribution within the treatment area, allowing precise and efficient therapeutic doses [109]. By optimizing heat transfer, MHD nanofluids contribute to reducing side effects and enhancing patient comfort during hyperthermia treatment, making them a promising technology for cancer therapy and other precise temperature-controlled medical treatments [110,111].

Sustainability and energy efficiency

The use of MHD nanofluids in various applications promotes sustainability and advances energy efficiency through a dual approach: decreasing total energy usage and reducing greenhouse gas emissions while conserving valuable resources. By enhancing heat transfer efficiency, MHD nanofluids enable the design of more energy-efficient cooling and heating systems, decreasing energy usage and diminishing greenhouse gas emissions. This aligns with the global drive to develop environmentally friendly and energy-efficient technologies, making MHD nanofluids a crucial component of the sustainable engineering landscape [112]. In the pursuit of sustainable engineering and energy-efficient technologies, MHD nanofluids play a vital role, conforming to worldwide initiatives to minimize ecological impact and advocate for sustainable resource utilization [97,98].

Current challenges, limitations, and future directions

The basic challenges and limitation to posed on MHD-NF forced convection experimental studies are discussed in this section after which the emerging trends and future direction were considered. Despite the challenges, ground −breaking results are achieved in this field of study as more innovative approach are generated by the day.

Current challenges in MHD-NF forced convection

The utilization of Magnetohydrodynamics (MHD) to enhance heat transfer in pipes and tubing presents several challenges. One key challenge involves the intricate optimization of magnetic field strength and fluid properties to attain maximal heat transfer improvement, which can be both experimentally complex and computationally demanding. As the need to generate optimized magnetic field strength and uniform magnetic field within the confined spaces of pipes and tubing potentially affects the overall effectiveness of MHD-NF augmented fluid flow and heat transfer.

Another associated challenge is the substantial energy consumption and infrastructure investments required for MHD-NF experiments. This makes it economically unfeasible for certain applications. The compatibility of the base-fluid and nanoparticle(s) in the nanofluids is critical for successful MHD applications. As this necessitates the resolution of issues like corrosion and nanoparticle sedimentation. Additionally, scaling up MHD systems for industrial use in large pipes introduces unique scaling effects distinct from laboratory setups, requiring innovative solutions and posing further challenges.

Some emerging trends

Advancements in MHD-NF within pipes and tubing call for a multifaceted research approach. Firstly, researchers are concentrating on the development of advanced nanofluids with enhanced thermal and magnetic properties, with a focus on optimizing nanoparticle characteristics like size, shape, and concentration. Secondly, the synthesis of magnetic nanoparticles must see continued improvement to enhance their responsiveness to magnetic fields with minimal agglomeration. Innovative pipe designs are also on the horizon, exploring optimized geometries that facilitate MHD processes to maximize heat transfer and fluid flow control.

While energy efficiency remains a key area for future research, striving to reduce the energy consumption associated with generating and maintaining strong magnetic fields within pipes to make MHD systems more sustainable. Additionally, the development of multiphysics simulations is crucial for gaining a comprehensive understanding of MHD's interplay with fluid flow, heat transfer, and magnetic field effects. These simulations could be used to predict MHD's real-world effectiveness in industrial applications like energy generation and heat exchangers, large-scale experimental studies and pilot projects before the actual work/experiment is done to cut down cost and time. Also, environmental impact of magnetic nanoparticles and nanofluids need to be considered, addressing issues related to disposal and long-term ecosystem effects.

Lastly, exploring the integration of MHD in pipes and tubing with clean energy sources, such as solar power systems, holds the promise of creating sustainable and efficient energy conversion systems.

Future directions and research gaps

Drawing from this review study on MHD-NF, there has been a notable interest among scholars in exploring the behaviour of individual magnetic nanofluids within pipes, ducts, tubing, and conduits when subjected to the influence of a magnetic field. There is a substantial body of work that has been conducted and documented in this specific field of study.

However, it is noteworthy that research on magnetic hybrid

Table 2
Overview of MHD of Hybrid Magnetic Nanofluids in Internal Forced Convection Flow pipes.

Authors	Magnetic nanofluids	Flow regime/ Reynolds number range	Magnetic field structure, type direction, intensity	Strategies for augmenting thermal efficiency
Lee et al. (2021) [65]	Fe_3O_4/MWCT/H_2O/EG	1000 to 1600	magnetic field intensity was adjusted to 250, 500, and 750 Gauss	The enhancement in particle volume concentration resulted observed, the maximum Convective Heat Exchange Rates exhibited increases of 2.78 % and 3.23 %, respectively.
Shahsavar et al. (2016) [89]	Fe_2O_4−CNTs/H_2O	548 to 2190	Magnetic field intensities were set at three levels: 300, 500, and 700 Gauss.	Elevating both particle density and magnetic field strength resulted the hybrid nanofluids in a maximum increase in 62.7 % of the local Nu
Tekir et al. (2022) [72]	Fe_3O_4 −Cu/H_2O	994 to 2337	constant/alternative, B = 0.3 T At a 90-degree angle to the flow direction	Increasing the magnet frequency and the in the presence of a continuous magnetic field, the maximum convective heat exchange saw a 14 % increase over the condition without a magnetic field
Shi et al. (2019) [90]	Fe_3O_4−CNTs/H_2O	60 to 540	The electromagnets were positioned horizontally at intervals of (0 mm, 50 mm, 100 mm, and 150 mm) while varying the rotation angles (0, 30, 60, and 120 degrees) and magnetic strengths (100, 200, 400, and 800 Gs).	As both particle volume concentration and magnetic field presence increased, the Mean heat exchange coefficient improved by 12.2 %. Furthermore, the local heat exchange coefficient showed a remarkable increase of over 30.2 % when a magnetic field was introduced.
Talebi et al. (2019) [91]	Fe_3O_4−Cu/H_2O	600 to 1800		As the particle volume concentration, Reynolds number, and magnetic field strength all increased, their research indicated a more substantial heat transfer enhancement with the hybrid-nanofluid, reaching 11.9 %, as opposed to 7.8 % for Cu/water.
Lee et al. (2021) [65]	Co −Zn −Fe_3O_4/H_2O	1000 to 1600	750 G magnetic field	The joint influence of increased particle volume concentration and the existence of a magnetic field led a heat exchange efficiency increase of approximately 2.64 % in contrast to the situation lacking a magnetic field.
Alsarraf et al. (2019) [66]	Fe_3O_4/MWCT/H_2O	500 to 2000	Three sets of NdFeB permanent magnets positioned with opposing poles directed towards each other are situated on both sides of the tube to create a three-dimensional magnetic field.	As volume concentration increased, they observed substantial improvements in the average Nu by 52.54 % and a remarkable 2376.4 % surge in pressure drag. Furthermore, the use of a magnetic field resulted in enhancements in both Nu and pressure drop.
Sadeghinezhad et al (2017) [92]	rGO/Fe_3O_4/DW		NdFe Permanent magnet 1320mT	82 % enhancement with the impact of a permanent magnetic field
Javadpour et al (2018) [93]	Cuo/CMC/H_2O	500–2000	Five permanent magnets with flux density of 50mT	13 % enhancement with 1 % volumetric ratio of nanofluid with the impact of magnetic field contrast to the situation lacking a magnetic field
Javadpour et al (2017) [94]	Cuo/CMC/H_2O	500–2000	Five permanent magnets with a flux density of 50mT	Utilizing an external magnetic field heightens nanofluid heat exchange, with a stronger influence at increased mass fractions. Nanofluids raise the annular tube's drag coefficient, with a 1 % volume fraction yielding a 22.6 % surge compared to the base fluid

nanofluids, which involve a combination of magnetic nanoparticles and other nanomaterials, remains limited and scarce. Only a few available studies have focused on assessing the convection-based heat transfer characteristics of a magnetic hybrid nanofluid flowing in the presence of a magnetic field., particularly in the laminar flow regime. A significant research gap exists on understanding the behavior of magnetic single and hybrid nanofluids subjected of a magnetic field in transition and turbulent flow regimes. These flow regimes are critical in practical applications, and the lack of comprehensive studies in this area represents an area for further investigation.

Moreover, there have been attempts to evaluate the effect of alternating magnetic fields on the convective heat exchange in single and hybrid magnetic nanofluid flows. However, a consensus has not yet been reached in the available literature concerning the dominance or excellence of a specific type of magnetic field (constant or alternating) in enhancing heat transfer. Some studies have suggested that a constant magnetic field has a more pronounced effect on heat exchange, while others have proposed that an alternating magnetic field can lead to an increased convective heat exchange efficiency.

In addition, the impact of increasing the intensity of the magnetic field on heat exchange has shown varying results in different reports. This conflicting information underscores the need for further research to adequately address these discrepancies and draw meaningful conclusions regarding the impact of magnetic fields on heat exchange in nanofluid flows. To achieve this, researchers should explore a wider range of parameters, including strength of the magnetic field and its frequency, to optimize the magnetic field configuration within pipes and tubing. Such optimization is essential to maximize its impact on fluid motion and thermal exchange in diverse real-world scenarios or applications.

Other areas in exploring the magnetic field effect in Magnetohydrodynamics (MHD) applications presents a diverse spectrum of research opportunities. These include optimizing magnetic field configurations within pipes and tubing for enhanced fluid flow and heat transfer, designing magnetic nanoparticles with tailored properties, and leveraging MHD for sustainable energy generation in renewable systems. Additionally, applying MHD in biomedical devices and cooling systems offers innovative solutions, while advancements in magnetic field generation, space exploration, and environmental remediation expand the field's horizons.

Ensuring materials compatibility, developing magnetic field sensors, fostering education, and promoting industry collaboration are pivotal in driving MHD research forward. With its multidisciplinary nature and wide-ranging applications, considering the magnetic field effect in MHD holds promise for transformative advancements across various sectors. Considering the magnetic field effect in MHD applications opens a wide range of possibilities for research and technological advancements, making it an exciting and multidisciplinary field with significant potential for the future.

Conclusion

This comprehensive review has bridged critical gaps in understanding the magnetohydrodynamic (MHD) behavior of nanofluid (NF) systems, with a focus on the dynamics of Fe_3O_4-based and hybrid nanofluids under varying magnetic field conditions, particularly within turbulent and transitional flow regimes. Drawing on an analysis of 141 experimental studies (2010–2024) and bibliographic data from the Scopus® database, this review elucidates how nanoparticle concentration, magnetic field intensity, frequency, and flow conditions synergistically influence heat transfer efficiency and flow stability.

Key findings demonstrate that MHD nanofluids significantly enhance heat transfer performance through the controlled manipulation of nanoparticle dispersion, clustering, and flow properties under magnetic fields. These mechanisms are vital for practical applications across diverse fields, such as energy systems, biomedical devices, and materials processing. Highlights of the review include:

i. **Enhanced Heat Transfer Mechanisms**
Alternating magnetic fields and optimized nanoparticle configurations lead to significant thermal performance improvements. For instance, studies by Zonouzi et al. and Hatami et al. demonstrated enhancements of 48.9 % and 60 %, respectively, underscoring the potential of magnetic nanoparticle alignment in augmenting heat transfer.

ii. **Tailored Magnetic Configurations**
The distinct effects of alternating and constant magnetic fields reveal that oscillating fields can offer up to 19.8 % enhancement (Yarahmadi et al.) within specific frequency ranges, whereas steady fields provide consistent improvements in certain applications. This variability emphasizes the need for case-specific optimization.

iii. **Flow Stability and Nanoparticle Dispersion**
Magnetic fields prevent nanoparticle agglomeration, ensuring uniform dispersion and thermal stability over extended operational periods. This property is crucial for systems requiring precise thermal control, such as electronics cooling and advanced HVAC technologies.

iv. **Pressure and Viscosity Modulation**
While MHD nanofluids improve thermal performance, increased pressure drops, such as the 54.5 % rise observed by Wang et al., highlight the necessity of balancing enhanced heat transfer with energy efficiency and mechanical feasibility in system design.

v. **Hybrid Nanofluids for Superior Performance**
Hybrid formulations, incorporating materials like multi-walled carbon nanotubes (MWCNT) or copper, demonstrate remarkable thermal enhancements. Shahsavar et al., for instance, reported a 62.7 % increase in local Nusselt numbers with Fe_3O_4-CNT hybrids, showcasing their potential in high-performance applications.

The practical implications of these findings are profound, spanning advanced cooling systems, renewable energy applications such as concentrated solar power (CSP), and high-precision biomedical devices like hyperthermia machines. Additionally, the adoption of MHD nanofluids in nuclear reactors, automotive cooling, and sustainable materials processing presents new pathways for energy-efficient and environmentally conscious engineering.

Looking ahead, this review identifies critical research gaps and sets a roadmap for future studies. These include:

- Investigating the behavior of hybrid nanofluids in turbulent and transitional flow regimes under magnetic field influence.
- Optimizing magnetic field configurations (intensity, frequency) for application-specific performance.
- Addressing challenges in scalability, environmental impact, and compatibility of nanofluids with industrial systems.

In conclusion, the insights synthesized in this review pave the way for transformative advancements in MHD nanofluid systems. By addressing the identified challenges and leveraging emerging trends, researchers and engineers can develop scalable, sustainable, and high-efficiency solutions for next-generation energy systems, materials processing, and thermal management technologies. These innovations hold the potential to reshape multiple industries, driving progress toward a more energy-efficient and sustainable future.

CRediT authorship contribution statement

Victor O. Adogbeji: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Emmanuel O. Atofarati:** Writing – original draft, Investigation, Formal analysis, Data curation. **Mohsen Sharifpur:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Josua P. Meyer:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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