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ABSTRACT

Magnetic permeability as a material property has a significant impact on the characteristics of a heated surface where induction heating or magneto-thermal systems are involved. In the heat and fluid flow mechanism where heat induction is used, magnetic permeability has a significant and crucial impact. Materials-like ferromagnetic materials with high magnetic permeability enhance the eddy current formation and can concentrate the magnetic field during the processes. These eddy currents lead to Joule heating in terms of electric current induced within the conductor by a changing magnetic field. Magnetic permeability also impacts the temperature profile within the material. Materials with extraordinary permeability due to the concentration of magnetic field can cause localized heating. The variable material properties in the presence of localized heating lead to non-uniform temperature distribution throughout the medium. In the magnetohydrodynamics heat and fluid flow region in the presence of magnetic permeability, some materials perform magnetostrictive impacts; therefore, they change shape or size under the influence of a magnetic field. The role of magnetic permeability along the heated surface is multifaceted in the system where an electromagnetic field is involved and affects how heat is generated, distributed, and dissipated. It is pertinent to mention that in the system where the electromagnetic field is involved, the magnetic permeability directly impacts the efficiency and uniform heating. Therefore, the understanding and controlling of magnetic permeability is important to design the systems that rely on exact thermal management, such as in magnetic shielding, magneto-thermal devices, and induction heating.

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I. INTRODUCTION

Magnetic permeability is a fundamental property of materials that measures up to which extent the material can be magnetized and how it deals with a magnetic field. It estimates the tendency of a material to maintain the materialization of a magnetic field within the material. During the processes for higher magnetic permeability, the more easily a material can become magnetized. Particularly in the presence of a magnetic field, the magnetic permeability can play an important role in various characteristics of heat and fluid flow processes. In moving fluids, Lorentz force is exerted by a magnetic field depending on the magnetic permeability of the fluid. Lorentz force can be used to control the thermal performance of the system for higher temperature. Therefore, the magnetic permeability is an important factor in the interaction between magnetic fields and heat and fluid flow mechanisms of the system under consideration. It impacts the characteristics of electrically conducting fluids and the efficiency of electromagnetic heating. Street *et al.*[1] provide an overview of studies conducted to ascertain how variations in the magnetic field supplied to the sample affect its magnetic

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viscosity, with two types of variations in the field being examined. Timur[2] created a basic model of permeable medium by extending the applications of nuclear magnetic resonance technologies and analyzing the pulsed NMR data. The low temperature irregularity in the spontaneous magnetization is described by Muxworthy and McClelland.[3] They examined the distinction between saturation and spontaneous magnetization close to the transition. Hydromagnetic convective heat transfer along permeable surfaces and porous mediums is discussed in Refs. 4–6. Comstock[7] highlighted a few technological issues that can prevent the growth in areal density along with the magnetic material utilized in the applications. In the context of blowing and suction, Seddeek[8] investigated the impact of both varying viscosity and magnetic field on non-Darcy forced convective flow across a flat surface with varying surface temperature in a permeable medium. It was discovered that as the rate of heat transmission dropped, the magnetic field enhanced wall skin friction. The mechanism of MHD heat and fluid flow from permeable different shapes with the inclusion of heat source/sink for thermophoresis chemical reaction is studied in Refs. 9–15. Ashraf *et al.*[16,17] studied the impacts of magneto-hydrodynamics and radiation on the buoyancy driven convective flow of conductive fluid across a vertically magnetized porous plate. They observed the impact of various physical parameters on the thermal transmission rate, current density, thermal profile, and skin friction coefficient along with fluid flow. The mechanism of viscous dissipation, ohmic heating, and conduction radiation in the presence of variable magnetic permeability is highlighted in Refs. 18–22. In consideration of the homogeneous chemical reaction, Sharma *et al.*[23] presented a magneto-hydrodynamics free convective flow of conductive micropolar fluid across a radiating surface along permeable media. The numerical and analytical solutions to the issues of magnetic permeability in the presence of a magnetic field are studied in Refs. 24–27. Taking into account the impact of ferro-magneto hydrodynamics, Kandelousi[28] considered the ferro-fluid flow and thermal transmission in the context of an externally applied changing magnetic field. The equations governing the system were solved using the control volume-based finite element technique. Free convective heat transfers along a vertical stretching sheet, magnetized vertical plate, and porous wedge for variable magnetic permeability are predicted in Refs. 29–34.

Chen *et al.*[35] demonstrated electromagnets with high permeability in multi-pole magnetic tweezers to quickly activate magnetic beads. Under the impact of squeeze velocity, Shah and Patel[36] investigated the influence of different and random permeable structures on the step bearing's performance when lubricated along with magnetic field. Selimli *et al.*[37] scrutinized the influence of the electromagnetic field on the thermophysical and hydrodynamic characteristics of magneto-viscous flow of fluid. The study of heat transfer for different thermophysical properties[38] has been studied in Refs. 39–42, numerically as well as analytically. In the presence of ferro-magnetohydrodynamics, the impact of a fluctuating magnetic field on forced convection thermal transmission in a semi annulus lid is explored by Sheikholeslami *et al.*[43] In permeable media, Salawu and Dada[44] examined the heat radiation of conductive fluid along a continually stretched surface with varying thermal conductivity and viscosity. In magnetic fluid, Afifah *et al.*[45] discussed the steadiness and accumulation of particles, emphasizing its special properties, including magneto-thermal convection and impacts of magnetic viscosity. Taking into account variable fluid's thermal conductivity and viscosity, a numerical solution for buoyancy force flow over a vertically magnetized surface is presented by Muhammad *et al.*[46] They solved the equations governing the problem by utilizing the finite difference technique and examined the influence of various flow parameters on the transverse magnetic field, fluid flow, and thermal profiles. The case of magneto-nanofluid heat transfer for porous curved surfaces and permeable stretching/shrinking surfaces has been studied in Refs. 47 and 48.

Chen *et al.*[49] used an experimental methodology for the inductive analysis of a varying flux permanent magnetic machine as well as a magnet frozen permeability finite element approach. They also presented a method for tracking the current trajectory bias with zero start DC. Numerical prediction of nanofluid convective heat transfer mechanism along porous shape for magnetic permeability has been carried out in Refs. 50–58. Hatami *et al.*[59] employed a finite element procedure with a commercial package (Flex PDE) to investigate the influence of a varying magnetic field on the buoyancy-induced convective thermal transport of magnetite–water nanofluid. The influences of an electric field in a permeable enclosure under the impact of thermal radiation were predicted in Ref. 60. Taking into account magnetic field and suction (blowing), Chaudhary and Choudhary[61] examined the impact of radiant heat and partially slip on the conductive fluid over stretching sheet. For the limited cases, they compared computational data for the non-magnetic model. The influence of magnetic field in half annulus cavity, heat sphere by means of obstacles, wavy channel, and permeable stretching surface has been analyzed in Refs. 62–67. Through experimentation, Cheng and Li[66] investigated the characteristics of ferro-fluid during natural convection heat transport while being subjected to a persistent magnetic field. Their study reveals that a decrease in cooling temperature ranged from 20 °C to −10 °C enhanced the performance and rate of thermal transmission for a 12 W heat load. Magnetohydrodynamics forced and free convective heat transfer around ellipse, porous inclined surface, and permeable stretching/shrinking sheet has been predicted in Refs. 68–72.

Contemplating the impact of magnetic heating, Khan *et al.*[73] analyzed the physical phenomena of natural convection nanoparticles along a sphere in the plume zone. The phenomenon of convective heat transfer for different classes of fluid for variable magnetic permeability along different complex geometries has been discussed in Refs. 74–80. Over a rotating surface, Shuaib *et al.*[81] studied the time-independent slip flow along convective thermal transmission under the impact of varying magnetic field and physical characteristics. Their findings suggest that the slip factor effectively regulates the flow and thermal properties. The features of fluid flow and heat in the manifestation of an induced magnetic field have been analyzed in Refs. 82–84. In a permeable channel, Marzougui *et al.*[85,86] considered the influence of hydromagnetic on the formation of entropy in time-dependent Poiseuille–Rayleigh–Bénard flow of conductive fluid. Along the influence of Arrhenius kinetics and Lorentz forces, Zhang *et al.*[87] considered the flow of nanoparticles over a nonlinear porous surface. Pishkar[88] and Almeshaal and Saha[89] explored the magnetic field's sway on the thermal transport enhancement and fluid flow properties. They presented the simulation's computational results regarding the various flow and contour parameters.

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The impact of heat source and sink in the presence of an aligned magnetic field in terms of heat and fluid flow along an electrically conducting cone surrounded by a porous medium is given in Ref. 90. In an innovative heat transfer system, varying magnetic fields' impact on the contaminant behavior of magnetic nanoparticles examined was by Fan *et al.*[91] Across a heated, non-conducting cylinder, Ullah *et al.*[92] tackled the consequence of hydromagnetics and low gravity on oscillatory buoyancy force conductive flow of fluid. Periodic scrutiny of convective heat transfers along cone entrenched in porous medium in Ref. 93 and second grade fluid flow using modified Fourier and Fick laws in Ref. 94 has been discussed, respectively. In a permeable medium, Ilyas and Ashraf *et al.*[95,96] presented the periodic nature of thermal transmission around a conductive cone. They determined the oscillatory behavior of heat transport, current density, and transient surface shearness. Considering the thermal and solutal slips, heat radiation, thermophoresis, and hydromagnetic effects, Nabwey *et al.*[97] discussed the simulation of reactive fluid transport in permeable media.

In the manifestation of magnetic flux and a catalyzed exothermic process, Ashraf *et al.*[98] explained the boundary layer behavior on the curved surface. It is noticed that the thermal profile rises sharply, whereas fluid flow and mass distribution steadily decline with the rise in the exothermic factor. Ullah *et al.*[99] analyze the impact of temperature dependent density and magnetic field numerically. Taking into account thermal radiation and magnetic field, Abbas *et al.*[100] demonstrated the low gravity's influence on thermal transport and fluid flow across a spherical surface placed in a permeable medium. Jalili[101] studied the non-linear radiative heat transfer with magnetic field. Considering the impact of thermal and flow slip, MHD and thermal transmission along the uniformly magnetized surface are analyzed by Alharbi *et al.*[102] The effects of reduced gravity and magnetohydrodynamics are discussed along different complex shapes in Refs. 102–104. On the free convection flow, Zeb Khan *et al.*[105] revealed the combined impact of fluctuating porosity and adiabatic wall movement. With the help of isotherms and streamlines, the impact of various physical parameters is explained. The impact of variable magnetic permeability, round vertical thermally stratified jet, triangular cavity, and infinite vertical moving plate has been discussed in Refs. 67 and 106–112. Computational analysis of magnetohydrodynamics fluid flow and heat transmission behavior in permeable cavities and Jeffery slip fluid flow in permeable linearly stretching sheets is discussed in Refs. 113 and 114. The system of partial differential equations established the heat and fluid flow mechanism in the presence of magnetic permeability by following[30] and is given as below:

$$\frac{\partial \overline{u}}{\partial \overline{x}} + \frac{\partial \overline{v}}{\partial \overline{y}} = 0, \tag{1}$$

$$\frac{\partial \overline{u}}{\partial \tau} + \overline{u}\frac{\partial \overline{u}}{\partial \overline{x}} + \overline{v}\frac{\partial \overline{u}}{\partial \overline{y}} = \frac{\partial^2 \overline{u}}{\partial \overline{y}^2} + \xi\left(\overline{h}_x \frac{\partial \overline{\mathrm{h}}_x}{\partial \overline{y}} + \overline{h}_y \frac{\partial \overline{\mathrm{h}}_x}{\partial \overline{y}}\right) - \Omega(\overline{u}) + \lambda\overline{\theta}, \tag{2}$$

$$\frac{\partial \overline{\mathrm{h}}_x}{\partial \overline{x}} + \frac{\partial \overline{\mathrm{h}}_y}{\partial \overline{y}} = 0, \tag{3}$$

$$\frac{\partial \overline{\mathrm{h}}_x}{\partial \tau} + \overline{u}\frac{\partial \overline{\mathrm{h}}_x}{\partial \overline{x}} + \overline{v}\frac{\partial \overline{\mathrm{h}}_x}{\partial \overline{y}} - \overline{h}_x \frac{\partial \overline{\mathrm{u}}}{\partial \overline{x}} - \overline{h}_y \frac{\partial \overline{\mathrm{u}}}{\partial \overline{y}} = \nu\sigma \frac{\partial}{\partial y}\left(\overline{\mu}\frac{\partial h_x}{\partial y}\right), \tag{4}$$

$$\frac{\partial \overline{\theta}}{\partial \tau} + \overline{u}\frac{\partial \overline{\theta}}{\partial \overline{x}} + \overline{v}\frac{\partial \overline{\theta}}{\partial \overline{y}} = \frac{1}{P_r}\frac{\partial^2 \overline{\theta}}{\partial \overline{y}^2}. \tag{5}$$

The dimensionalized boundary conditions are

$$\begin{aligned} &\overline{u} = \overline{v} = 0, \quad \overline{h}_y = 0, \quad \overline{h}_x = 1, \quad \overline{\theta} = 1 \quad at \quad \overline{y} = 0, \\ &\overline{u} \to \overline{U}(\tau), \quad \overline{\theta} \to 0, \quad \overline{\mathrm{h}}_x \to 0 \quad as \quad \overline{y} \to \infty. \end{aligned} \tag{6}$$

Here, $\gamma = \overline{\mu}\sigma\nu$ is the magnetic Prandtl number, and $\overline{\mu}$ is variable magnetic permeability. In electromagnetically active materials, both magnetic and thermal properties play roles in the following way:

$$\overline{\mu}(T) = \overline{\mu}_\infty\left[1 + \alpha_1\left(\frac{T - T_\infty}{T_w - T_\infty}\right)\right].$$

Here, $\overline{u}$ and $\overline{v}$ are the x and y components of velocity, $\overline{h}_x$ and $\overline{\mathrm{h}}_y$ are the x and y components of magnetic field, Ω, λ, and σ are porous parameters, mixed convection parameters, magnetic and electrical conductivity, respectively.

The impact of magnetic permeability on different characteristics of heat and fluid flow mechanisms is given below.

A. Impact of magnetic permeability on thermal conductivity of the material

From the closed study of the literature and from the characteristics of both properties, that is, magnetic permeability and thermal conductivity of the material, it is found that there is no direct, intrinsic relationship between them in heat and fluid flow mechanisms. However, in some physical phenomena where these two properties are important, as a secondary impact, one property can directly affect the other. In composite materials, those used in electromagnetic shielding with thermal management capabilities are optimized through both properties. It is important to point out here that magnetic permeability and thermal conductance are normally independent properties. However, in some special cases, such as some advanced materials or for some specific applications, an understanding of how these characteristics interact in a particular way can be required. Therefore, the influence of magnetic permeability on thermal conductance is normally slight and indirect, but for some specific applications, it could be important.

B. Impact of magnetic permeability on magnetized shielding

Keeping in view the above-mentioned literature review, the magnetic permeability shows a significant role in the impactness of magnetized shielding to save the system from excessive heating. Magnetized shielding is the mechanism of delaying or lessening magnetic fields using blockades made of conductive or magnetized materials. It is important to save sensitive electronic devices from electromagnetic intrusion. Furthermore, the shielding impact depends on the material's tendency to absorb or release electromagnetic rays. In this mechanism, there are two types of shielding: low frequency shielding and high frequency shielding. For low frequencies, magnetic fields can penetrate most of the materials and are more difficult to shield. The material belonging to high magnetic permeability, such as mu-metal, can absorb and release magnetic current effectively and save them from passing through the shielding. In the case of higher frequencies, the skin effect becomes more

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significant for high magnetic permeability and, therefore, the thickness of the shielding material for magnetic fields, thereby improving adequately. We summarize the significance of magnetic permeability on magnetized shielding that the low frequency magnetic fields are harmful, and high permeability materials are important and favorable for establishing effective magnetized shielding.

C. The skin depth and magnetic permeability

In heat and fluid flow processes, the skin depth measures how effectively an electromagnetic ray can enter into a conductive material before it is meaningfully reduced. For increasing values of electromagnetic frequency, the skin depth is reduced, which means that the electromagnetic rays penetrate less deeply. On the other hand, the materials with higher electrical conductivity and higher magnetic permeability have a smaller skin depth, leading to a greater decrease of electromagnetic waves. Moreover, we define the skin depth as inversely proportional to the square root of magnetic permeability. From this understanding, it is concluded that the materials with large magnetic permeability will have a low skin depth and, therefore, the electromagnetic waves are confined near the surface and lead to a very thin layer of penetration. These are the special applications of magnetized shielding for the designing of inductors and transformers. These concepts are very important in different applications, such as radio frequency technology and material science.

D. Impact of magnetic permeability on transverse motion

The motion of the charge particle is due to the impact of the magnetic field; therefore, the magnetic force acts normal to both the velocity of the charge particle and the magnetic field direction. This normal force can lead the particle to track a curved path, leading to normal motion, which is designated as transverse motion. In materials with greater magnetic permeability, the induced magnetic field within the material is resilient to the same magnetic field applied to the surface. This resilient magnetic field increases the Lorentz force acting on the charges in motion, thereby the magnetic permeability enlarging the transverse motion within the domain under consideration. Therefore, the permeability of the materials impacts how efficiently the magnetic fields can be used to switch the motion of charged particles. Materials with upper permeability can cause stronger detention and a more accurate mechanism of transverse motion during magnetized heat and fluid flow processes. The spreading of electromagnetic waves in materials is also swayed by the magnetic penetrability, such as in waveguides or resonant cavities; the transverse electromagnetic types are pretentious by the permeability, which determines the phase velocity profile and impedance of the wave's motion. It is pertinent to mention that the magnetic permeability meaningfully influences the transverse motion in magnetic fields by manipulating the magnitude of the magnetic field within a material, which consequently affects the magnetic forces acting on moving charges or current density. This connection is crucial in many scientific applications, such as electromagnetic waveguide systems, magnetic detention systems, and devices relying on accurate control of particle motion in magnetic fields. The impact of magnetic permeability is given in Ref. 20. It is predicted that for increasing values of transpiration, the current density is decreased, as shown in Fig. 1.

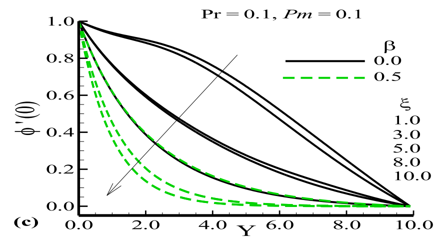

FIG. 1. Impact of transpiration in the presence of a magnetic field on current density.

E. Impact of magnetic permeability on current density

The materials for which the magnetic field is changed can cause the eddy currents and are induced within the material through which the charge particle is transmitted. The scale of these induced changes depends on the rate of change of the magnetic field and the material's magnetic permeability. For higher magnetic permeability, the induced current is higher for large magnetic fields. The higher magnetic permeability of the core material increases the magnetic flux association, which leads to higher current densities in the windings due to the higher induced electromagnetic force. If the magnetic permeability of the material is variable and depends on the magnetization of the material, it leads to non-linear behavior, which develops the complex relationship between the magnetic field and current density. The phenomenon of magnetic permeability has its crucial influence on current density in many electromagnetic contexts. If the magnetic permeability of the material is increased, it can produce more pronounced induced current near the surface. We summarize the discussion by saying that the relationship between magnetic permeability and current density is important to designing efficient electromagnetic devices such as inductors, transformers, and conductors. Ashraf *et al.*[16] have concluded the results as given in Table I for the impact of magnetic permeability on current density. From this table, it is evident that the magnetic permeability reduced the current density in the presence of electromagnetic rays. The impact of thermal radiation along a magnetized permeable plate in the presence of magnetic permeability is given in Ref. 16 and is predicted in Table I.

TABLE I. Impact of magnetic permeability parameter ξ on current density for different values of radiation parameter Rd.

ξ	$Rd = 1.0$	$Rd = 10.0$
0.05	1.350 80	1.376 91
0.1	1.307 72	1.330 24
1.0	0.769 50	0.777 77
3.0	0.323 95	0.324 14
5.0	0.188 62	0.188 55
10.0	0.087 58	0.081 00

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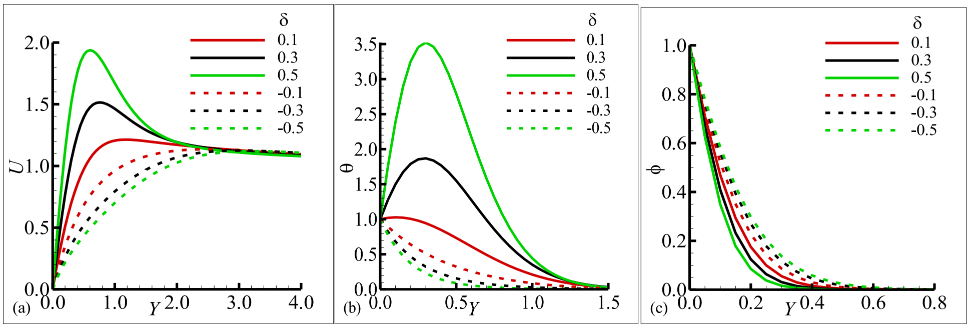

FIG. 2. Geometrical interpretation of heat source and sink in the presence of magnetic field.

F. Impact of magnetic permeability on heat source and sink

The impact of magnetic permeability can be applied in heat sink problems to design the devices for the removal of heat from structures by interchanging the magnetic fields in order to absorb and dissipate heat. The materials with high-permeability are frequently used for system shielding to protect components from externally applied magnetic fields. Such materials act like heat sources due to magnetic damage. Basically, effective heat sinks or thermal management strategies are employed to manage the heat generated within the shielded components during processes. For strong magnetic fields, the permeability of the materials must be used and considered. In magnetohydrodynamics problems where weak magnetic permeability of the materials is involved, such as aluminum or copper, they are considered heat sinks because they significantly interfere with magnetic fields. In these mechanisms, the heat is dissipated effectively without affecting the magnetic system's performance. The impact of heat source and sink in the presence of an electrically conducted cone embedded in porous has been predicted in Ref. 90 and is given in Fig. 2.

II. CONCLUSION

From the understanding of the above-mentioned literature review, it is concluded that the impact of magnetic permeability on heat and fluid flow mechanisms is very complex and is critical for various industrial applications. Furthermore, it is concluded that the magnetic permeability where aligned magnetic fields interact with fluids can reduce the convective heat transfer and increase the heat conduction. In this study of the literature review, we have the following findings.

The significance of magnetic permeability on magnetized shielding is that the low frequency magnetic field is harmful, and high permeability materials are important and favorable for establishing effective magnetized shielding. The influence of magnetic permeability on thermal conductance is normally slight and indirect, but for some specific applications, it could be important. It is concluded that the materials with large magnetic permeability will have a low skin depth and, therefore, the electromagnetic waves are confined near the surface and lead to a very thin layer of penetration. The permeability of the materials impacts how efficiently the magnetic fields can be used to switch the motion of charged particles. If the magnetic permeability of the material is variable and depends on the magnetization of the material, it leads to non-linear behavior, which develops the complex relationship between the magnetic field and current density. The higher magnetic permeability of the core material increases the magnetic flux association, which leads to higher current densities in the windings due to the higher induced electromagnetic force. If the magnetic permeability of the material is variable and depends on the magnetization of the material, it leads to non-linear behavior, which develops the complex relationship between the magnetic field and current density. The materials with high-permeability are frequently used for system shielding to protect components from externally applied magnetic fields. Here, it is pertinent to mention that the material and literature highlighted in this review will be fruitful for researchers, scientists, and academicians to establish new theories and ideas in the field where magnetic field is important.

III. FUTURE RECOMMENDATIONS

There are many opportunities for further research and development in the rich field of magnetic permeability in relation to heat and fluid flow characteristics, especially in applications involving magnetized shielding. The following suggestions are for further research in this field:

- Examine novel materials with specific magnetic permeability characteristics that can preserve thermal conductivity while improving shielding efficacy. Composites and nanostructured materials may fall under this category.
- Examine materials with temperature-dependent magnetic permeability that provide dynamic shielding in a range of thermal conditions.
- Create sophisticated CFD models that integrate fluid flow dynamics, heat transport, and magnetic field effects. This will make it easier to comprehend how the Lorentz force affects thermal distribution and flow patterns in magnetically protected situations.
- Use multiscale modeling techniques to capture the relationships between macroscopic fluid flow and heat transfer events and the microstructural characteristics of materials.
- To maximize thermal management and efficiency, investigate how magnetic permeability affects heat and fluid flow in renewable energy systems, such as geothermal or solar thermal collectors.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

All authors have equal work. All authors have read and agreed to the published version of the paper.

Hossam A. Nabwey: Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Methodology (equal); Project administration (lead); Writing – original draft (equal); Writing – review & editing (equal). **Muhammad Ashraf**: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **A. M. Rashad**: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Writing – review & editing (equal). **Ali J. Chamkha**: Conceptualization (equal); Formal analysis (equal); Investigation (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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