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By: **Abed Mourad**

**THEME**

# Effect of an external magnetic field on natural convection in a porous medium

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# ABSTRACT

Heat transfer is one of the most fundamental and essential engineering principles. Heat transfer is used in some way in almost every sector. To either add or remove heat from a system, a heat transfer medium, including solids and fluids are employed. Since they are adaptable and versatile, fluids are employed extensively. However, the conventional heat transfer fluids (HTF) employed in industry have poor thermal properties. Thus, they have a limited ability to transport heat. In recent years, a new class of HTF called nanofluids (NFs) have been developed. These engineered fluids have enhanced thermal properties making them the future of HTF. In order to better comprehend the impact of different factors on nanofluid flow and heat transfer behavior, a detailed analysis of a nanofluid natural convection within a porous enclosure exposed to a magnetic field has been conducted. Additionally, specific research has been conducted to look at how entropy is generated in nanofluid natural convection flow. the mathematical model explaining this phenomenon has been constructed. The resulting non-dimensional equations have been discretized using the Galerkin weighted residual technique of finite element formulation.

In this thesis, the steady-state incompressible free convection flow of nanofluid in two enclosures was investigated using computational fluid dynamics (CFD) software. The first enclosure is square with elliptical heated hole in the center and cold wavy sidewalls. The second one is an annulus space formed by a heated Koch-snowflake-shaped cylinder and a cooled circular cylinder. The numerical results are presented for the effects of Rayleigh numbers (Ra) from $10^3$ to $10^6$, Hartman number (Ha) from 0 to 100, Darcy number (Da) from $10^{-5}$ to $10^{-2}$, geometrical parameter (undulation number and inner cylinder position) solid volume fractions 0, 2%, 3%, 4%, 5% and 8% on the distributions of isotherms, streamlines, average Nusselt number (Nuavg) as well as on total entropy generation and Bejan number (Be).

The findings suggest that the addition of nanofluid under certain conditions, increased heat transmission. Also, the maximum heat transfer increase was recorded in the conduction dominated flow regime, where the increased thermal characteristics of nanofluids play a key role. When convection is the major heat transfer mode, utilizing nanofluids offers a lesser improvement in heat transfer efficiency. The computational outputs reveal that raising the Ra number which is feasible by varying the temperature between the hot and cold sources, boosted the buoyant force. Thus, raising the value of Ra enhances the natural convection flow and improves the average Nusselt number. Furthermore, it is discovered that for large Ra numbers the average Nusselt number is more susceptible to the other factors. Implementing Lorentz force, if not in the direction of natural flow, forces the flow velocity to be depleted. As the Da number grows, the penetration of the flow cross-section in the cavity rises, and the flow circulates in the cavity with less depreciation.

**Keywords:** *Convective heat transfer, Magnetohydrodynamic, CFD, Hybrid Nanofluid, Porous media, Galerkin finite element technique, Wavy wall, Koch snowflake.*

# RÉSUMÉ

Le transfert de chaleur est l'un des principes d'ingénierie les plus fondamentaux et les plus essentiels. Le transfert de chaleur est utilisé d'une manière ou d'une autre dans presque tous les secteurs. Pour ajouter ou retirer de la chaleur d'un système, un milieu de transfert de chaleur, comprenant des solides et des fluides, est utilisé. Puisqu'ils sont adaptables et polyvalents, les fluides sont largement utilisés. Cependant, les fluides caloporteurs classiques utilisés dans l'industrie ont de mauvaises propriétés thermiques. Ainsi, ils ont une capacité limitée à transporter la chaleur. Ces dernières années, une nouvelle classe de fluides caloporteurs appelée nanofluids (NF) a été développée. Ces fluides techniques ont des propriétés thermiques améliorées, ce qui en fait l'avenir des fluides caloporteurs. Afin de mieux comprendre l'impact de différents facteurs sur le comportement d'écoulement et de transfert de chaleur d'un nanofluid une analyse détaillée de la convection naturelle d'un nanofluid dans une enceinte poreuse exposée à un champ magnétique a été menée. De plus, des recherches spécifiques ont été menées pour examiner comment l'entropie est générée dans le flux de convection naturelle des nanofluid. Le modèle mathématique expliquant ce phénomène a été construit. Les équations non dimensionnelles résultantes ont été discrétisées en utilisant la technique des résidus pondérés de Galerkin de formulation par éléments finis.

Dans cette thèse, le flux de convection libre incompressible à l'état d'équilibre d'un nanofluid dans deux enceintes a été étudié à l'aide d'un logiciel de mécanique des fluides numérique (CFD). La première enceinte est carrée avec un trou chauffant elliptique au centre et des parois latérales ondulées froides. Le second est un espace annulaire structuré par un cylindre en forme d'un Koch-snowflake et un cylindre circulaire refroidi. Les résultats numériques sont présentés pour les effets des nombres de Rayleigh (Ra) de $10^3$ à $10^6$, nombre de Hartman (Ha) de 0 à 100, nombre de Darcy (Da) de $10^{-5}$ à $10^{-2}$, paramètre géométrique (nombre d'ondulation et position du cylindre) fractions volumiques solides 0, 2%, 3%, 4%, 5% et 8% sur les distributions des isothermes, lignes de courant, nombre de Nusselt moyen (Nuavg) ainsi que sur la génération d'entropie totale et le nombre de Bejan (Be).

Les résultats suggèrent que l'ajout de nanofluid dans certaines conditions, a augmenté la transmission de chaleur. En outre, l'augmentation maximale du transfert de chaleur a été enregistrée dans le régime d'écoulement dominé par la conduction, où les caractéristiques thermiques accrues des nanofluid jouent un rôle clé. Lorsque la convection est le principal mode de transfert de chaleur, l'utilisation de nanofluid offre une moindre amélioration de l'efficacité du transfert de chaleur. Les sorties de calcul révèlent que l'augmentation du nombre Ra, qui est réalisable en faisant varier la température entre les sources chaude et froide, a stimulé la force de flottabilité. Ainsi, l'augmentation de la valeur de Ra améliore le flux de convection naturelle et améliore le nombre de Nusselt moyen. De plus, on découvre que pour les grands nombres Ra, le nombre moyen de Nusselt est plus sensible aux autres facteurs. La mise en œuvre de la force de Lorentz, si ce n'est dans la direction de l'écoulement naturel, force la vitesse d'écoulement à s'épuiser. Au fur et à mesure que le nombre Da augmente, la pénétration de la section d'écoulement dans la cavité augmente et l'écoulement circule dans la cavité avec moins d'amortissement.

**Mots-clés :** *Transfert de chaleur convectif, Magnétohydrodynamique, CFD, Nanofluide hybride, Milieu poreux, Technique des éléments finis de Galerkin, Paroi ondulée Koch snowflake.*

# ملخص

يعد نقل الحرارة أحد المبادئ الهندسية الأساسية. يتم استخدام نقل الحرارة بطريقة ما في كل قطاع تقريبًا. لإضافة أو إزالة الحرارة من النظام ، يتم استخدام وسط نقل الحرارة ، بما في ذلك المواد الصلبة والسوائل. نظرًا لأنها قابلة للتكيف ومتعددة الاستخدامات ، يتم استخدام السوائل على نطاق واسع. ومع ذلك ، فإن سوائل نقل الحرارة التقليدية المستخدمة في الصناعة لها خصائص حرارية رديئة وبالتالي ، لديهم قدرة محدودة على نقل الحرارة. في السنوات الأخيرة ، تم تطوير فئة جديدة من سوائل نقل الحرارة تسمى السوائل النانوية. هذه السوائل المصممة هندسيًا تملك خصائص الحرارية محسنة مما يجعلها مستقبل سوائل نقل الحرارة .من أجل فهم تأثير العوامل المختلفة على تدفق السوائل النانوية وسلوك نقل الحرارة بشكل أفضل ، تم إجراء تحليل مفصل للحمل الحراري الطبيعي للسائل النانوي داخل حاوية مسامية معرضة لمجال مغناطيسي. بالإضافة إلى ذلك ، تم إجراء بحث محدد للنظر في كيفية إنشاء الانتروبيا في تدفق الحمل الحراري الطبيعي للسائل النانوي. تم بناء النموذج الرياضي الذي يشرح هذه الظاهرة. تم تقدير المعادلات غير الأبعاد الناتجة باستخدام تقنية (ڤرلكان) الموزونة المتبقية لصياغة العناصر المحدودة.

في هذه الأطروحة ، تم فحص التدفق الحراري الحر غير القابل للضغط للحالة المستقرة للسائل النانوي في حاويتين باستخدام برنامج ديناميكيات السوائل الحسابية . العلبة الأولى مربعة الشكل بها ثقب بيضاوي ساخن في المنتصف وجدران جانبية مموجة باردة. والثاني عبارة عن فضاء حلقي يتكون من أسطوانة ساخنة على شكل ندفة ثلجية من نوع كوخ وأسطوانة دائرية مبردة. تم عرض النتائج العددية لتأثيرات أرقام رايلي من $10^3$ إلى $10^6$ ، ورقم هارتمان من 0 إلى 100 ، ورقم دارسي من$10^{-5}$ إلى $10^{-2}$ ، والمعامل الهندسي (رقم التموج والداخلي) وضع الأسطوانة) الكسور ذات الحجم الصلب 0 ، 2٪ ، 3٪ ، 4٪ ، 5٪ و 8٪ على توزيعات متساوي الحرارة ، الانسياب ، متوسط عدد نسلت وكذلك على إجمالي توليد الكون وعدد البيجان.

تشير النتائج إلى أن إضافة مائع النانو في ظل ظروف معينة ، زاد من انتقال الحرارة. أيضًا ، تم تسجيل أقصى زيادة في نقل الحرارة في نظام التدفق المسيطر عليه التوصيل ، حيث تلعب الخصائص الحرارية المتزايدة للسوائل النانوية دورًا رئيسيًا. عندما يكون الحمل الحراري هو الوضع الرئيسي لنقل الحرارة ، فإن استخدام السوائل النانوية يوفر تحسينًا أقل في كفاءة نقل الحرارة. تكشف المخرجات الحسابية أن رفع رقم رايلي وهو أمر ممكن من خلال تغيير درجة الحرارة بين المصادر الساخنة والباردة ، عزز قوة الطفو. وبالتالي ، فإن رفع قيمة رايلي يعزز تدفق الحمل الطبيعي ويحسن متوسط عدد نسلت. علاوة على ذلك ، تم اكتشاف أنه بالنسبة لأعداد رايلي الكبيرة ، يكون متوسط عدد نسالة أكثر عرضة للعوامل الأخرى. إن تنفيذ قوة لورنتز ، إن لم يكن في اتجاه التدفق الطبيعي ، يفرض استنفاد سرعة التدفق. مع نمو رقم دارسي ، يرتفع تغلغل المقطع العرضي للتدفق في التجويف ، ويدور التدفق في التجويف بأقل استهلاك



**الكلمات المفتاحية:** *نقل الحرارة بالحمل الحراري ، مغناطيسي هيدروديناميكي ، ديناميكا الموائع الحسابية ، سائل نانوي هجين ، وسائط مسامية ، تقنية العناصر المحدودة من* ڤرلكان ، جدار مموج ، *ندفة ثلجية كوخ.* .

# Nomenclature

| List of symbols | |
|---|---|
| B | Magnetic induction (T) |
| $B_0$ | Magnetic field strength ($A.m^{-1}$) |
| Cp | Heat capacity ($J.kg^{-1}.°C^{-1}$) |
| Da | Darcy number |
| $d_p$ | Average particle or fiber diameter (m) |
| g | Acceleration due to gravity ($m.s^{-2}$) |
| h | Heat transfer coefficient ($W.m^{-2}.K^{-1}$) |
| h | Heat transfer coefficient ($W.m^{-2}.K^{-1}$) |
| Ha | Hartmann number |
| K | Permeability ($m^2$) |
| k | Thermal conductivity ($W.m^{-1}.K^{-1}$) |
| $k_{eff}$ | Effective thermal conductivity ($W.m^{-1}.K^{-1}$) |
| L | Characteristic length (m) |
| N | Undulation number |
| Nu | Nusselt number |
| P | Dimensionless pressure |
| p | Pressure (Pa) |
| Pr | Prandtl number |
| $\Delta P/L$ | Pressure gradient in the direction of flow ($Pa.m^{-1}$) |
| q | Heat flux by convection ($W.m^{-2}$) |
| Ra | Rayleigh number |
| T | Temperature (K) |
| $T_\infty$ | Ambient temperature (K) |

| | |
|---|---|
| $T_w$ | Wall temperature (K) |
| $\Delta T$ | Temperature difference (K) |
| U, V | Dimensionless velocity magnitude |
| u, v | Dimensional velocity components ($m.s^{-1}$) |
| $V_D$ | Darcian velocity ($m.s^{-1}$) |
| Vs | Volume of the solid phase ($m^3$) |
| **Greek symbols** | |
| $\varphi$ | Solid (nanoparticles) volume fraction |
| $\alpha$ | Heat diffusion coefficient ($m^2 .s^{-1}$) |
| $\beta$ | Thermal diffusion coefficient ($k^{-1}$) |
| $\varepsilon$ | Porosity |
| $\mu$ | Dynamic viscosity ($kg. m^{-1} .s^{-1}$) |
| $\mu_{eff}$ | Effective dynamic viscosity ($kg .m^{-1} .s^{-1}$) |
| $\nu$ | Kinematic viscosity ($m^2 .s^{-1}$) |
| $\rho$ | Fluid density ($kg .m^{-3}$) |
| $\theta$ | Dimensionaless temperature |
| $\sigma$ | Electrical conductivity ($S.m^{-1}$) |
| $\lambda$ | Permeability of the medium. ($H.m^{-1}$) |
| **Subscript** | |
| c | Cold |
| eff | Effective |
| f | Fluid (base fluid) |
| h | Hot |
| s | Solid (nanoparticles) |
| nf | Nanofluid |
| np | Nanoparticles |

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# Introduction

# Introduction

One of the most crucial industrial processes is heat transmission. Heat must be effectively managed in many industrial processes via addition, subtraction, or transformation. Improved heat transfer efficiency enhances the effectiveness and durability of equipment while also saving time and energy. Many studies have been conducted to better comprehend the mechanisms of heat transfer. Modern thermal management methods are more in demand than ever as high-tech applications with substantial heat dissipation emerge. Conventional thermal management systems that depend on heat transfer fluids such as water, ethylene glycol (EG), pumping oil, etc, are showing unsatisfactory performances owing to the weak thermal conductivity of these fluids. Therefore, the development of highly efficient heat transfer fluids to overcome the limitation of traditional fluids has become one of the most significant tasks in thermal management research.

In 1995, Choi, a scientist at Argonne National Labs, devised a remarkable approach to improve the thermal properties of heat transfer fluids. Choi showed that adding a modest number of metal nanoparticles (nano-sized particles) to a fluid dramatically increased the fluid's capacity to conduct heat. Because of the particles' order-of-magnitude size drop, they exhibit much greater colloidal stability. Choi established the term “nanofluid” to label a liquid containing a dispersion of nanoparticles with a typical length raging from 1 to 50 nm. nanofluid extraordinary properties and advantages make them the most promising next-generation cooling fluids. Furthermore, additional potential strategies are applied to boost thermal management performance such as porous materials. This technology is frequently employed in various technical applications such as heat exchangers, geothermal energy systems, and filtration devices. Porous medium promotes heat transfer by enhancing the flow mixing owing to the zigzag routes in the porous media and extending the contact surface with the cooling fluid.

The purpose of this thesis is to explore the natural convection heat transfer of nanofluid saturating a porous medium and subjected to a uniform magnetic field. To accomplish this, two distinct studies have been carried out utilizing computational fluid dynamics software. It's vital to analyze this phenomenon to understand the influence of nanoparticles concentration, Rayleigh number, porous medium, and magnetic field on the heat transfer and the flow.

Chapter 1 gives a basic review of natural convection, porous materials, and magnetohydrodynamics. After that, nanofluids are introduced and several of their aspects are examined such as their emergence, their manufacturing process, and their possible uses and advantages. This chapter also includes a literature overview of studies conducted on nanofluids flow and heat transfer in various enclosures under diverse circumstances such as porous medium and magnetic field.

Chapter 2 describes the mathematical model notably the Navier-Stokes equations that regulate the single-phase incompressible fluid flow and natural convection heat transfer within an enclosure. In addition, the numerical approach applied to solve the mathematical model is introduced.

Chapter 3 will be devoted to the presentation and discussion of the various dynamic and thermal findings. numerical investigations are carried out using single phase approach to analyze the heat transfer and steady magneto-hydrodynamic natural convection in an enclosure with cold corrugated walls incorporating a hot and centered elliptical cylinder and partitioned into two layers. Here, the influence of buoyancy forces, magnetic field, porous media, nanoparticles concentration, and undulations number on flow, and heat transfer are presented.

Chapter 4 will discuss the natural convection heat transfer behaviors of (Fe3O4-MWCNT) nanofluid flow through horizontal annulus filled with porous medium and subjected to magnetic field. The novelty of this work is presented by the special shape and different studied positions of the hot inner tube. Here, the influence of buoyancy forces, magnetic field, porous media, nanoparticles concentration, and inner tube position on flow, heat transfer, and entropy production are presented.

Finally, conclusions and perspectives are stated in the general conclusion.

# Chapter I: Generalities and Literature review

# Generalities and Literature review

## 1. Introduction

This Chapter gives a basic review of the main aspect of this thesis. First natural convection, porous materials, and magnetohydrodynamic are briefly discussed. After that, nanofluids are introduced and several of their aspects are examined such as their emergence, their manufacturing process, and their possible uses and advantages.

## 2. Generalities

### 2.1. Heat transfer mechanism

Temperature differences can cause energy to move from one system to another in the form of heat. Evaluating this energy transfer rate is a key aspect of the study of heat transfer. Heat always passes from a medium with a higher temperature to one with a lower temperature, and when the two mediums reach the same temperature, heat transmission stops. Heat transfer requires a temperature gradient in all situations. Heat can be transmitted using three different mechanisms: conduction, convection, and radiation. In essence, the distribution of heat in a system is determined by the interplay of these three types of heat transport. Below we give a brief description of convection mode [1].

#### 2.1.1. Convection

The convective mode, in which the relative velocity of the fluid provides an additional mechanism for the transmission of heat and materials, has attracted substantial attention in the range of studies associated with heat transfer. Its study is the study of convective heat transfer allows us to evaluate the energy the fluid will convey in the system and it is connected to fluid dynamics and heat transport. In fluids, convection and conduction are intricately related because, despite the fact that fluid motion affects the transport mechanism, heat inevitably flows from one fluid element to another in its proximity through conduction [2].

Convective heat transfer has two branches: natural convection is when the driving force of the fluid flow arises spontaneously owing to the temperature differential. Which separates it from Forced convection when the heat transport is impacted by driven fluid motion created by external forces

The natural convection process, where the flow is created by the gravitational field and buoyant forces caused by the density difference, is the main subject of this thesis. Without the intervention of an external force, these forces induce fluid flow. Since temperature changes have an impact on the fluid's density, which leads to the development of buoyant forces, it is essential to have at least two hot and cold sources in the system. Since the intensity of the fluid currents in natural convection depends on the severity of the temperature gradient itself, measuring natural convection heat transfer qualitatively and quantitatively is very difficult. Numerical analysis is thus more useful in this area than theoretical analysis [3], [4].

The fundamental principle governing heat transfer by convection is Newton's law of cooling. The rate of heat transfer by natural convection is governed by this equation, which asserts that heat transmission is proportional to the temperature difference [5].

$$q = h \times \Delta T \qquad (1.1)$$

where q is heat flux by convection ($W.m^{-2}$), h is heat transfer coefficient ($W.m^{-2}.K^{-1}$), and ΔT is temperature difference.

Convection heat transfer studies mostly use two non-dimensional numbers to characterize natural convection. The first, referred to as the Nusselt number (Nu), quantifies the fraction of convective to conductive heat transfer across a fluid's boundary.

$$Nu = \frac{h}{k / L} = \frac{hL}{k} \qquad (1.2)$$

where h is the convective heat transfer coefficient of the flow($W.m^{-2}.K^{-1}$), L is the characteristic length (m), and k is the thermal conductivity of the fluid ($W.m^{-1}.K^{-1}$) .

The second is the Rayleigh number (Ra), which is associated with the buoyancy-driven flow. It defines the fluid's flow regime; values in the higher range reflect turbulent flow, while values in the lower range denote laminar flow. Moreover, below a specific value of Ra, there is no fluid motion, and conduction rather than convection is used to transport heat.

### 2.1.2. Natural convection in enclosures

a) Rectangular enclosures

A space heater inside a rectangular room relies on natural convective currents to heat the room and is a good example of natural convection inside a rectangular enclosure as seen in Figure 1.

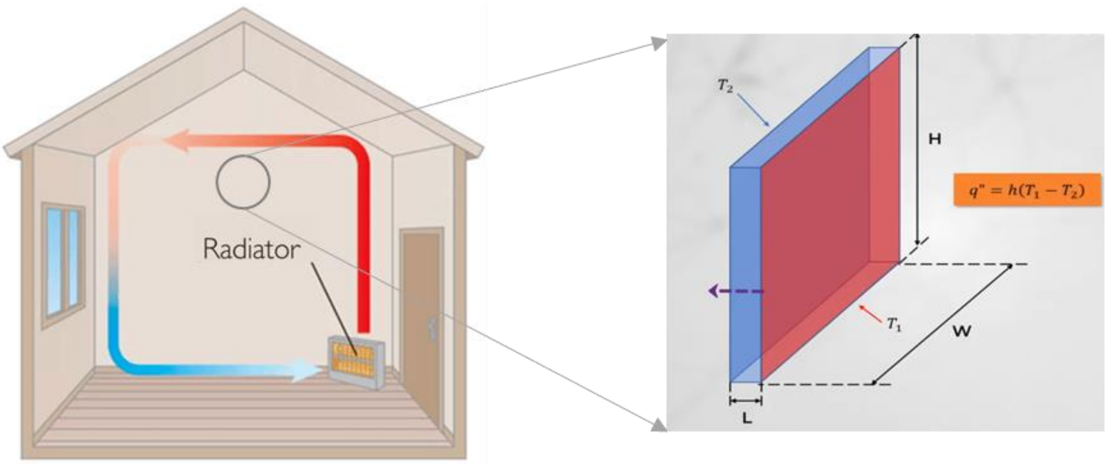



*Figure 1 Natural convection inside a room (rectangular enclosure)*

Consider a rectangular cavity with dimensions L, W, and H. In this cavity, the two opposite walls are at temperatures $T_1$ and $T_2$ as highlighted in Figure 1, such that $T_1 > T_2$. The other 4 walls of the cavity as assumed adiabatic. This temperature difference is responsible for natural convection, and the total heat flux transferred across the cavity is given by the following relationship.

When the cavity is viewed from the side, the height of the cavity (H) is at a tilt angle $\tau$ with the horizontal plane. When this tilt angle is 0, the cavity is horizontal, and the bottom wall is heated. When $\tau$ = 90 degrees, the cavity is vertical with the sidewall heated as shown in Figure 2. The heat transfer due to natural convection in a horizontal cavity is very different from the vertical. In addition to the tilt angle, the overall heat flux in these enclosures also depends on the aspect ratios of the cavity – H/L and W/L.

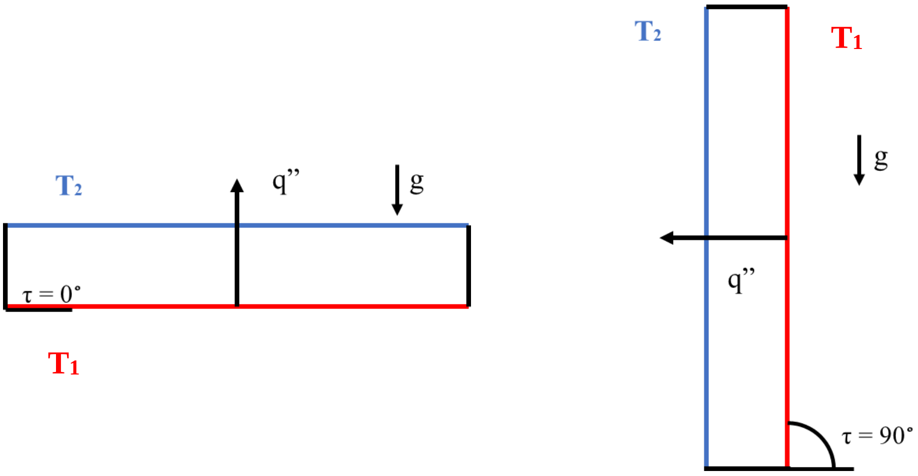



*Figure 2 Horizontal and Vertical rectangular cavity*

The fluid flow behavior is a strong function of the Rayleigh number – the non-dimensional number which dictates when a flow transitions to turbulence. For thin slender cavities with H/L and W/L >> 1 and Rayleigh numbers lower than a critical value of 1708, the buoyancy forces are not strong enough to overcome the viscous resistance offered by the fluid (viscous forces > buoyancy forces). Under these conditions, there is no advection of fluid and the primary modes of heat transfer across the cavity are conduction and radiation (if any). The Nusselt number in this scenario is approximately equal to 1. As the Rayleigh number increases beyond the critical value of 1708, the buoyancy force due to the density difference between the hot and cold fluid regions can overcome the viscous resistance experienced by the fluid. The fluid begins to circulate inside the cavity and the overall heat transfer is augmented because of the natural convection.

In horizontal enclosures, for modest Rayleigh numbers ranging between 1708 and $5\times10^4$, an interesting flow pattern is observed inside the rectangular cavity. The motion of the fluid creates a pattern of uniformly spaced counter-rotating roll cells within the cavity as seen in Figure 3. This uniform pattern of fluid motion transitions to turbulence at larger Rayleigh numbers.

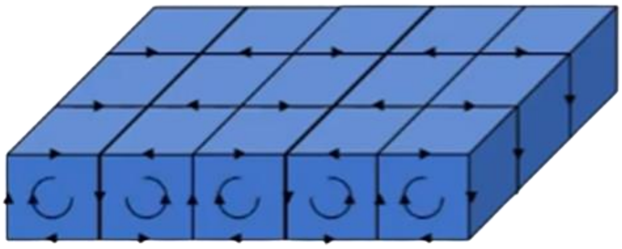


*Figure 3 Counter-rotating roll cells*

Finally, no natural convection can exist when the top wall is at a higher temperature compared to the bottom wall (see Figure 4). This implies that the only modes of heat transfer inside a rectangular cavity with a tilt angle of 180 degrees are conduction and radiation (if any).

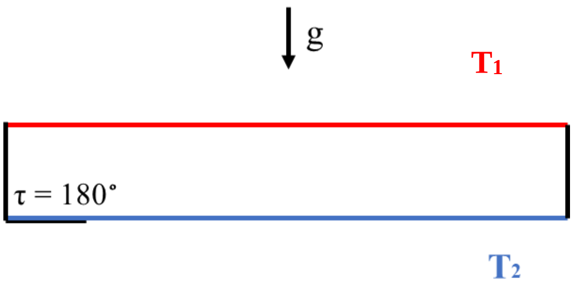



*Figure 4 Horizontal rectangular cavity with τ=180°*

Similar observations can be made in the case of vertical rectangular cavities (τ = 90 degrees). In this case, two of the opposing sidewalls are maintained hot and cold. The other four walls, including the top and bottom, are adiabatic. Until a critical Rayleigh number of about $10^3$, the buoyancy force is not strong enough to overcome the viscous resistance and the Nusselt number is approximately equal to 1. As the Rayleigh number increases beyond $10^3$, a recirculating flow is observed inside the vertical enclosure such that the fluid rises and falls near the hot and cold walls, respectively, as shown in Figure 5.

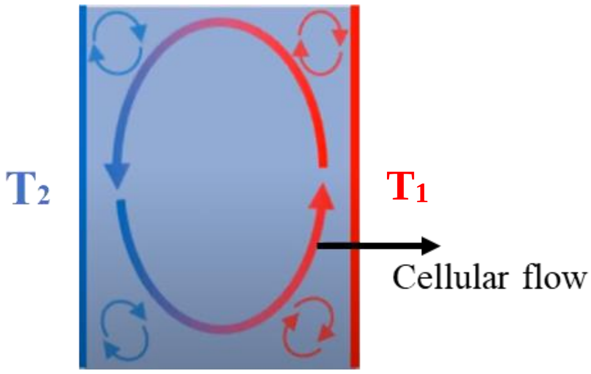



*Figure 5 Cellular flow*

This cellular flow in the enclosure is stronger near the boundary layer regions closer to the hot and cold walls. The fluid is relatively stagnant in the core region of the cavity. It is important to highlight that additional cells can develop near the corners of the enclosure. As the Rayleigh number increases further, the fluid flow transitions to turbulence.

b) Concentric cylinders enclosures.

In cylindrical boiler heating water, the inner cylinder is considered the heating element. In this example, before water starts to boil, the heat transfer is primarily driven by natural convection inside a concentric cylindrical enclosure. As shown in Figure 6, heat is transferred between the inner and outer cylinders across the annular space between them. The circulation of fluid in this space depends on whether the inner cylinder is hotter or colder compared to the outer cylinder.

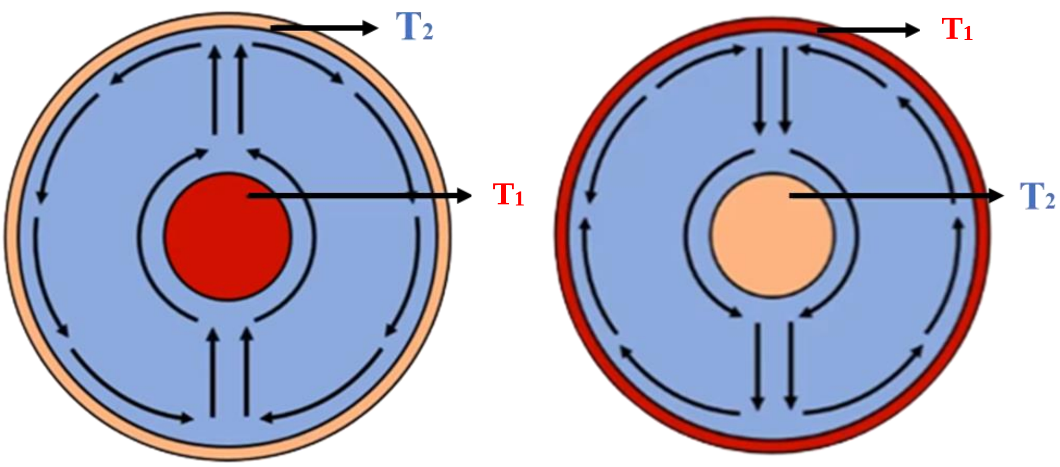



*Figure 6 Convection flow inside annulus enclosure*

When the inner cylinder is hotter compared to the outer $T_2 > T_1$, the fluid moves in the cavity such that it rises along the inner cylinder wall and falls along the outer cylinder wall. This motion creates a recirculating region inside the annular space between these cylinders as shown in the lest side of Figure 6. This motion is reversed if the outer cylinder is hotter compared to the inner ( right side of Figure 6).

### 2.2. Magnetohydrodynamic

Magnetohydrodynamics (MHD), commonly known as magnetofluid dynamics or hydromagnetics, is the study of the behavior of electrically conducting fluids. liquid metals, electrolytes, salt water, and plasmas, are a few examples of these fluids. The term "magnetohydrodynamic" refers to magnetic fields, liquids, and movement, respectively. In 1970, Hannes Alfvén received the physics Nobel Prize for establishing the field of MHD [6]. The fundamental principle of MHD is that magnetic fields may induce currents in moving conductive fluids, which in turn impose forces on the fluid and change the magnetic field. The set of equations governing MHD is composed of the fluid dynamics Navier-Stokes equations and the electromagnetism Maxwell equations. These differential equations must be simultaneously solved, either numerically or analytically.

The Lorentz force law is the foundation of the MHD model. A charged particle traveling in an electromagnetic field is subjugated to a force, according to the Lorentz force equation [7]. This force may be described as:

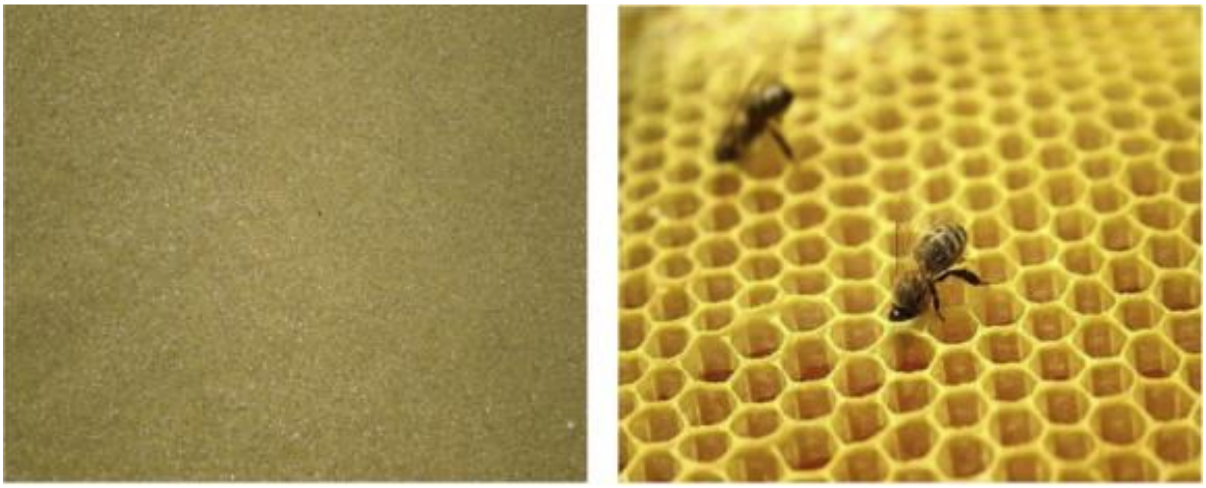
$$\vec{F} = q\left(\vec{u} \times \vec{B}\right) \tag{1.3}$$

where $\vec{F}$ is the force acting on a charged particle, q is the charge of the particle, $\vec{u}$ is the velocity of a particle, and $\vec{B}$ is the magnetic induction.

## 2.3. Porous material

Another intriguing strategy for heat transfer improvement in industrial systems is the employment of porous media, for example, the utilization of metal-based porous materials such as copper foams in pipes of heat exchangers [8].

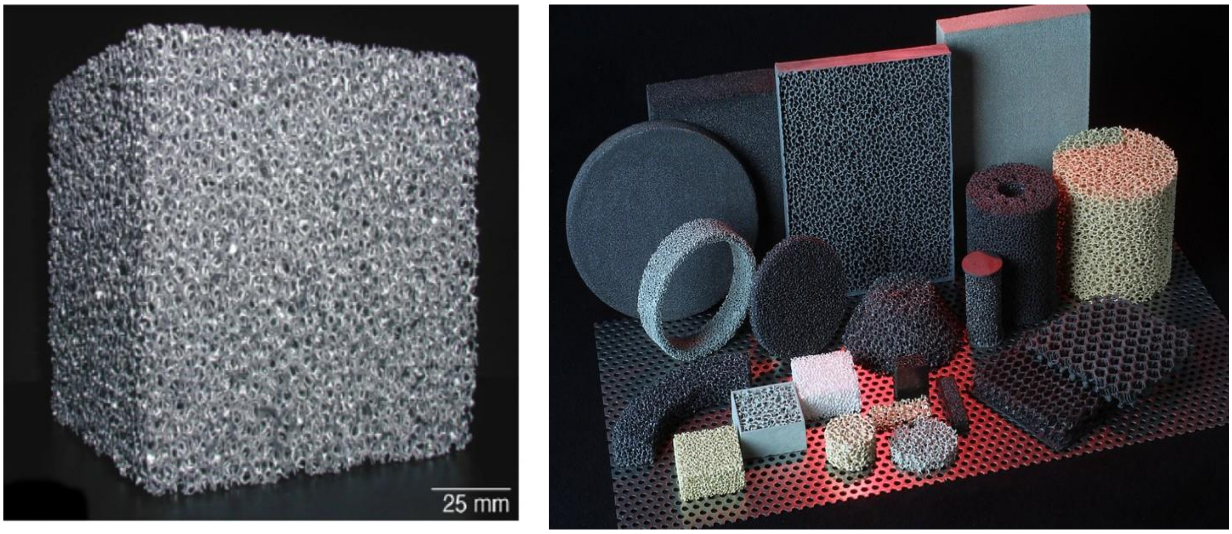
Porous medium (material) are solids, which are penetrated by a network of pores. Fluid may move through the porous material because of how the pores are connected. In both nature and industry, porous materials are quite common. Examples of naturally occurring porous media limestone, sandstone, wood, rye bread, and the human lung might be given. Metallic and nonmetallic foams, packed beds, and porous ceramics are examples of man-made porous media that are often utilized in industrial applications [9], [10]. Heat exchangers are where metallic foams are often employed. Figure 7 and Figure 8, respectively, show natural porous media: (a) porous sand (b) honeycomb, and industrial porous media: (a) aluminum foam utilized in heat exchangers and packed bed in energy storage applications (b) porous ceramics employed in filters, absorbers, dust collectors, thermal insulation.



(a) (b)

*Figure 7 Natural porous media: (a) porous sand (b) honeycomb [11]*

### 2.3.1. Fluid Flow in Porous Media




*(a)* *(b)*

*Figure 8 Man-made porous media: (a) aluminum foam (b) porous ceramics [12]*

Fluid flow through a porous medium is present to some extent in various science and engineering sectors including filtration, separation, purification, mechanics (acoustics, geomechanics, soil mechanics, rock mechanics), material science, biology, biophysics geosciences (geophysics, hydrogeology, petroleum geology), and engineering (construction engineering, petroleum engineering, bioremediation, heat transfer) [13]–[15].

Due to the intricate structure of porous media and the complicated interactions between the fluid and solid phases, flow in porous materials is exceedingly complicated. The flow parameters (velocity, pressure, temperature, etc.) on the pore scale will be distinctly erratic. Furthermore, the narrow and intricate flow route geometry found inside the pores makes local, on-site evaluations of fluid dynamics at the pore level particularly challenging. In order to study fluid and heat transmission in porous media, theoretical studies based on solving the Navier-Stokes equation are often utilized. The pore-scale method and the continuum method are the two major methods for theoretically modeling the flow of fluid and the transfer of heat in porous media.

### 2.3.2. Darcy's Law

For a very long time, fluid flow through a porous medium has been researched. When he looked at the fluid flow through packed sand, Darcy was the first to establish a linear connection between pressure drop and flow rate. Following a modification to add the fluid viscosity [16], the relationship, often known as Darcy's law, is expressed as follows [2]:

$$-\frac{\Delta P}{L}=\frac{\mu V_D}{K} \tag{1.4}$$

where V is the Darcian velocity ($m.s^{-1}$), μ isthe viscosity of the fluid ($kg.\ m^{-1}.s^{-1}$), K is the permeability of the porous media ($m^2$), and ΔP/L is the pressure gradient in the direction of flow.

the Darcian velocity equals the volume flow rate divided by the entire cross-section area of the entire porous medium. It is easy to draw the conclusion that in a porous medium, viscous force predominates the flow in Darcy flow. Many researchers have confirmed that Darcy's rule only applies when a single-phase fluid is flowing through a porous medium at a sufficiently slow rate.

The most well-known functions that depict the connection between pressure drop and velocity in porous media are Darcy's law, Forchheimer-extended Darcy equation, and Ergun equation. Other academics have also looked for novel functions for the correlation [17], [18].

#### 2.3.3. Effects of Fluid and Structure Factors on Porous Flow

The essential Reynolds number of regimes, the pressure drop, and even the distribution of the velocity field are all significantly influenced by the structural properties of the porous medium. Effects of porosity, particle size, pore shape, and flow property on the fluid flow dynamics within the porous structure are studied extensively in the literature [19]–[21].

a) Porosity

The porosity of a porous material is a geometrical attribute defined as the percentage of total media occupied by empty spaces. The higher the porosity, the more pores, and less solid restrictions there are in the structure, enabling fluid to flow more easily. One of the most important elements influencing porous flow behavior is porosity [22]. If the entire volume of the medium and the solid volume are known, porosity may be defined as follows.

$$\varepsilon = 1 - \frac{V_s}{V_t} \tag{1.5}$$

where ε is the porosity, Vs is the volume of the solid phase ($m^3$), and Vt is total volume of the medium ($m^3$).

b) Permeability

The ease with which a fluid will flow through a porous media is measured by its permeability; the greater the permeability, the higher the flow rate for a given pressure differential. The Carman-Kozeny theory may be used to determine the permeability as shown below [23].

$$K = \frac{\varepsilon^3 d_p^2}{180(1-\varepsilon)^2} \tag{1.6}$$

where dp is the average particle or fiber diameter (m).

### 2.3.4. Mechanisms of Heat Transfer in Porous Metal

Due to their high thermal conductivity, porous metals have excellent heat conduction through their solid matrix. The structure of the matrix and the thermal conductivity of each phase affect how much heat may be conducted through a matrix that is completely saturated with fluid (like air in porous metals). Metals with pores have a significant surface area-to-volume ratio, which is ideal for heat convection. Heat convection in porous metals with open cells is improved by greater flow mixing brought on by turbulence and tortuous channels. Four processes may contribute to heat transmission in a porous metal: convection through a liquid phase, conduction through a liquid phase, conduction through a solid phase, and radiation [24].

Natural Convection in Porous Metals

The buoyancy effect may cause flow when the temperature of the saturated fluid phase in a porous material is not constant. Generally speaking, convective motions that tend to homogenize the whole fluid volume where they occur have two major effects: they enhance overall heat transmission and generate a temperature distribution that is not uniform and has hot and cool zones [25].

Because of their huge surface area, porous metals have recently emerged as an alternate structure to increase surface area, due to their appealing qualities, including large surface area, high thermal conductivity, and low density. Recently, the method of employing both nanofluid and porous media has drawn a lot of interest and prompted in-depth research on this subject. On the one hand, porous media increase the area of contact between a liquid and a solid surface, while on the other, nanoparticles distributed in nanofluid improve the heat conductivity effectively. It seems that utilizing both porous medium and nanofluid may significantly increase the efficiency of conventional thermal systems [26].

### 2.4. Nanofluid

High heat transfer cooling systems are necessary for several technologies, including high-speed microprocessors, laser application equipment, superconducting magnets, and heat exchangers. Existing thermal fluids with poor thermal conductivities can no longer match the demands of high-intensity heat transmission due to the growing heat transfer rates needed by current heat exchange systems [27], [28]. The development of very compact and efficient heat exchangers is primarily constrained by the low thermal properties of the heat transfer fluids. Many methods have been suggested to improve heat transmission in this kind of equipment. Suspending tiny solid particles in fluids is an efficient approach to increasing the thermal conductivity of certain fluids [29]. Historically, thermal liquids were mixed with solid particles that were millimeter or micrometer-sized. Though the solid additives may increase the heat transfer coefficient, their usefulness is limited because the micrometer- or millimeter-sized particles settle quickly, obstruct flow channels, degrade pipelines, and result in pressure decreases. Because of these underlying issues, this approach is not appealing from an industrial standpoint [30].

A novel class of possible heat transfer fluids called nanofluids was first described by researchers at Argonne National Laboratory in 1995. They are made by suspending metallic or nonmetallic particles with a nanoscale in a base fluid [31]. By developing nanofluids (NFs) during the last ten years, nanoscience and nanotechnology have provided a fresh approach to the problem of improving the performance of heat transfer fluids, particularly in high-tech applications. The thermal conductivities of nanofluids are notably greater than those of traditional pure fluids, according to several experimental findings, and they offer a promising prospect for improving heat transmission. Since nanofluids suffer little to no pressure drop because the nanoparticles are so small (typically less than 100nm), they behave like pure fluids, they are better suited for the practical application than existing techniques for enhancing heat transfer such as adding millimeter and/or micrometer-sized particles in fluids [32]. Additionally, due to their tiny diameters, nanoparticles are less prone to cause wear. NFs are more stable than fluids that include micro- or millimeter-sized particles, and they are also more capable of transferring heat than their base fluids. These characteristics provide significant advantages for a wide range of applications in different sectors. The future generation of various engineering applications will be considerably enhanced by the improvements in thermal management made possible by nanofluids in terms of cost, overall design, reliability, and performance [33], [34].

The following are the primary factors that led to this improvement in heat transfer efficiency by nanofluids:

a) The fluid's mixing fluctuation and turbulence are amplified.

b) The dispersion of nanoparticles reduces the transverse temperature gradient of the fluid.

c) The fluid's heat capacity and surface area for heat transmission are both increased by the dispersed nanoparticles.

d) The fluid has more effective thermal conductivity due to the nanoparticle suspension.

e) The collision and interaction of nanoparticles, fluid, and the flow passage surface are enhanced.

The literature suggests that NPs might include ceramic compounds like sulfides, oxides, and carbides, as well as metallic/intermetallic compounds (such Cu, Ag, Fe, Ni, etc.). Carbon-based substances, such as carbon nanotubes, graphite, graphene, etc, may also be used to create nanostructured materials. Water, ethylene glycol (EG), water and EG mixed (W/EG), coconut oil, kerosene, diethylene glycol (DEG), paraffin, polyethylene glycol, gear oil, vegetable oil, pump oil, etc. are all examples of base liquids [35], [36].

The thermal conductivities of several metals and fluids are shown in Figure 9 From this, it may be inferred that adding metals to traditional fluids, which have greater thermal conductivities than those fluids, might result in an increase in the total heat transfer coefficient.

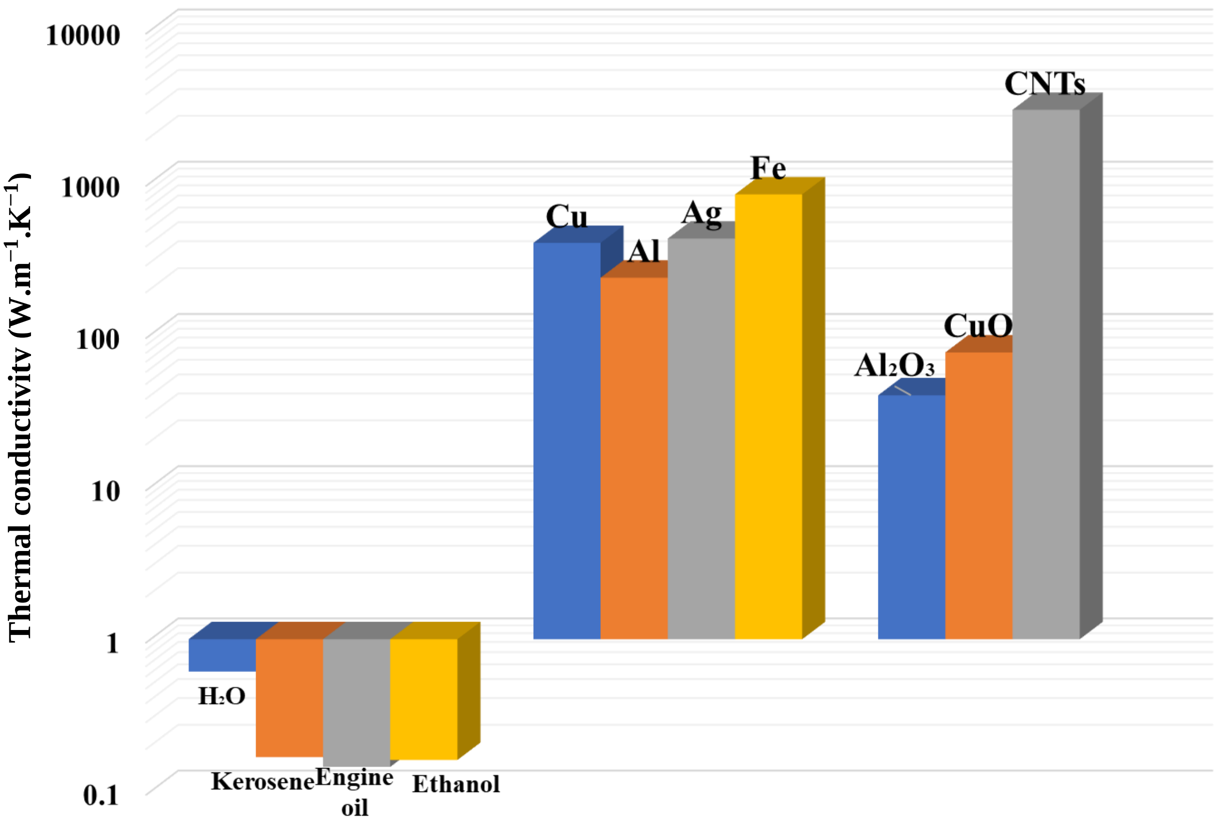



*Figure 9 Thermal conductivity of some metals, nonmetal, and base fluids [35], [36]*

### 2.4.1. NFs and their applications

Since the debut of the NF idea more than 10 years ago, the potential of NFs applications in several fields has drawn growing interest. In a number of thermal systems, nanofluids may be employed to increase energy efficiency and heat transmission. The majority of the work being done on the topic of nanofluids is being done at academic institutions and national labs and is beyond the discovery research stage. More companies are now actively working on developing nanofluid technology for certain industrial applications as they become more aware of its potential [26], [37], [38]. Some of the possible uses of NF in various fields are shown in Figure 10


*Figure 10 Different applications of NFs*

The potential for NFs to be used in heat transfer applications has garnered the greatest interest among all of their applications. In the transportation sector, ethylene glycol plus water, the practically ubiquitous vehicle coolant, performs comparably poorly to water alone as a heat transfer fluid. The cooling rates of automobile and heavy-duty engines might be increased by adding nanoparticles to the conventional engine coolant. A smaller coolant system may be employed to remove engine heat with this modification [39]. Microprocessors and integrated circuits' power densities have significantly grown recently in the field of electronics. In the near future, the tendency should continue. Nanofluids are leading contenders to replace the current air-cooling and liquid-cooling methods for extracting this heat, which has recently reached their limitations [40].

NFs have been employed in a variety of biomedical and nanomedicine applications, including nano-drug delivery, cancer treatments, sensing, and imaging, and nano-cryo-surgery, according to the literature [41]. Some NFs have been developed and effectively used in the enhanced oil recovery (EOR) process, anticorrosive coatings, wettability modification, and drilling technology, among other non-renewable energy industries like the petroleum industry. Furthermore, the amazing potential of NFs for usage in surface coating, environmental remediation, lubrication, inkjet printing, metal processing, and fuel additives is shown in many papers. The ability of NFs as energy storage media has been reported in some studies in the literature, including the fabrication of advanced phase change materials (PCM) for thermal energy storage and solar absorption, where NFs could improve the absorption property of the traditional working fluid in solar collectors [42].

### 2.4.2. NFs preparation methods

It must be noted that making NFs involves more than just mixing and spreading solid ingredients in a base liquid. The most important step in using NPs or any other nanostructured materials to improve the thermal properties of traditional heat transfer fluids is the synthetization process. The reason is that improper preparation of the NFs may cause the agglomeration of solid particles in base fluid media, which may then lead to poor thermo-physical properties of the NFs. A number of techniques have been put forward to make nanofluid suspensions. One-step and two-step preparation are the two primary categories that these techniques often fall under [43].

### a) Preparation of NFs via a two-step method

The two-step process, which is the most widely utilized method, starts with the physical or chemical synthesis of NPs as dry particles. Then, as illustrated in Figure 11, the produced dry nano-powders are scattered in base liquids by ultrasonication.

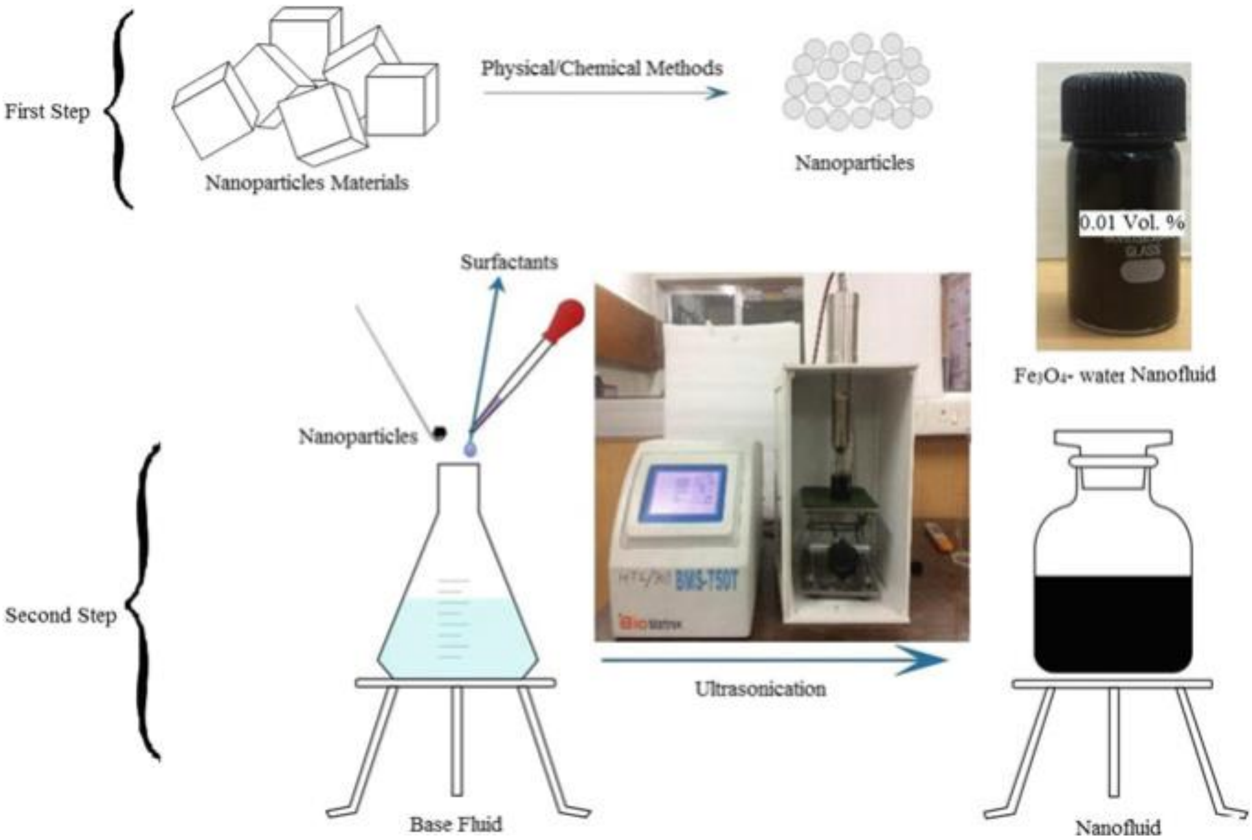



*Figure 11 Fe3O4-Water nanofluids prepared using a two-step process.*

This approach is the best option for producing NFs on a big scale since solid NPs and nanostructures have previously been made in commercial quantities. However, agglomeration/aggregation of NPs is inevitable due to the high surface activity of nanoparticles. Therefore, this approach allows for the possibility of NP sedimentation, which has a detrimental impact on the NF's qualities [44].

b) Preparation of NFs via a one-step method

In the one-step preparation, the nanoparticles are manufactured and then instantly dissolved in the base fluid. Either a liquid chemical technique or physical vapor deposition may be used to accomplish this. Physical vapor deposition involves vaporizing a solid metal and condensing the resulting metallic vapor into a low-vapor-pressure liquid. A chemical reaction is used in a liquid chemical approach to directly produce nanoparticles in the base fluid. The typical advantage of creating nanofluids via a one-step preparation process is that dry nanoparticle aggregation is reduced [45].

#### 2.4.3. Thermo-physical properties of NFs

In order to evaluate the effectiveness of an NF for heat transfer applications, one needs to consider the thermo-physical parameters of NF including thermal conductivity, viscosity, density, specific heat as well as the flow regime of the fluid. NFs systems are complex suspension and their thermo-physical and transport characteristics like thermal conductivity, viscosity and heat transfer coefficient (HTC) may be affected by several factors [46].

a) Thermal Conductivity of NFs:

Thermal Conductivity is the most crucial thermo-physical feature of NFs, which must be researched in order to establish the competence of these innovatively designed suspensions for thermal management applications.  This characteristic effects the Nusselt and Prandtl numbers; both present the heat transport properties of a liquid flow. Higher thermal conductivity is required for effective NFs for thermal management applications [47].

b) Viscosity of NFs:

It is vital to highlight that having a high relative Thermal Conductivity value solely is not adequate for employing an NF as an effective heat transfer fluid (for cooling purposes). In order to pick the efficient NF with the best qualities for cooling applications, not only thermal conductivity but also viscosity must be examined. Viscosity plays a significant part in all thermal applications involving flowing fluids and it is characterized by the internal resistance of a fluid to flow. After the addition of NPs to the base liquid, the viscosity of NFs is predicted to be higher than their base liquids; nevertheless, this rise causes a detrimental impact on the pumping power and HTC [48].

#### 2.4.4. Advantages of Nanofluids

The nanofluid offers impressive outcomes for heat transmission enhancement in a variety of applications. The following are the benefits of suspending nanoparticles into the standard base fluids [49]:

- The fluid's actual thermal conductivity will be greatly increased.
- Highly applicable to the current system without significant changes.
- The thermophysical characteristics may be changed to suit the requirements of various applications.
- The fluid's stability is improved.
- Increased nanoparticle mobility results in significant heat transfer.
- Increasing the surface-to-volume ratio of nanoscale particles improves heat transmission.
- Nanoparticles cause less particle agglomeration and flow loop blockage.

#### 2.4.5. Types of Nanofluids

The nanofluids may be grouped in a variety of ways; generally speaking, they can be grouped as indicated in Figure 12. The classification is defined as follows.

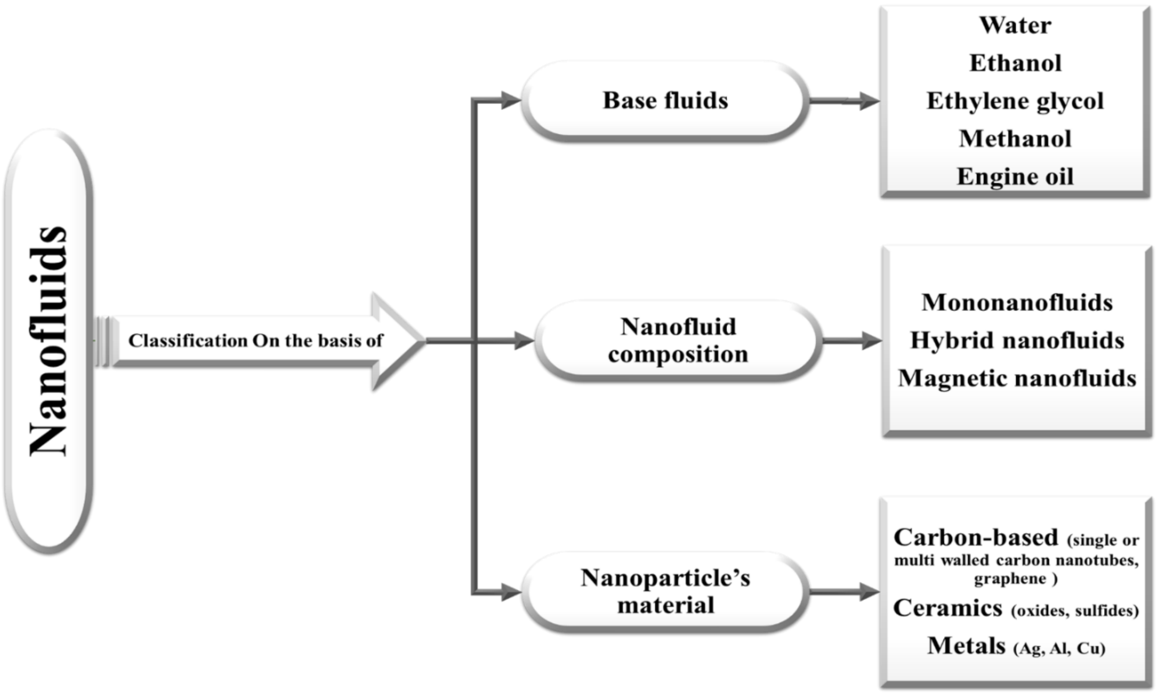



*Figure 12 Classification of the nanofluids*

a) On the basis of base fluids

To enhance the thermophysical characteristics, the nanoparticles are dissolved in the base fluids. For the dispersion of such nanoparticles, many base fluids are available. The researcher has utilized water extensively in their investigations of nanofluids.

b) On the basis of nanoparticle's material

The materials of the nanoparticles include metals (gold, copper, silver, aluminum, etc.), metal oxides (CuO, Al2O3, ZnO, Fe2O3, etc.), and carbon-based (carbon nanotubes, graphite, diamond, etc.). Numerous research has examined the impact of different nanoparticle types on the functionality and thermophysical characteristics of conventional base fluids.

c) On the basis of nanofluid composition

A single component, a mixture, or a combination of two or more components may make up the nanomaterials scattered in a fluid. The amount of heat transferred by the nanofluid will inevitably rely on the dispersed nanoparticles, which in turn will depend on its fundamental nanoscale characteristics. A combination of two or more components out of which one is in nanoscale, usually known as a nanocomposite is simply an effort to produce synergism in most scenarios. It is crucial for this that the necessary nanocomposite material be properly chosen and synthesized in order to get the desired result. According to the makeup of the dispersed nanomaterial, nanofluids can be divided into standard and hybrid types.

A. Standard nanofluids or mononanofluids

The standard sort of nanofluids known as mono-nanofluids are nanofluids as they have been first established, which generally consist of a single nanomaterials component spread throughout the fluid phase. Any of the nanomaterials covered in Section 1.4.1, in varying concentrations and sizes, may make up this liquid. As a result of the simplicity involved, the nature—or rather, behavior—of the nanomaterials is restricted to the only element present.

B. Hybrid nanofluids

The development of "hybrid nanofluids," which employ two or more components that are either individually present in the nanofluid or bound to one another, was prompted by the growing need for nanofluids with enhanced characteristics. Additional reasons for the development of the concept of nanofluids toward the creation of hybrid nanofluids include agglomeration in pure metal-based nanofluids and lower thermal transport in metal oxide-based nanofluids [46].

C. Magnetic nanofluids (ferrofluids)

Extensive research has been done on magnetic nanofluids (MNFs), a colloidal suspension of ferromagnetic nanomaterial. After considering its unique eximious qualities and distinctive intriguing properties, it provides a wide range of applications, not only in the field of heat transfer but also hugely prominent in the medical, biological, aerospace, electronics, and solar sciences. MNFs are a unique category of nanofluids with magnetic and fluid characteristics.

# 3. Literature review

The thermal performance and characteristics of nanofluids have been the subject of several experimental or numerical studies. Figure 13 shows that, from 1995 to 2022, there was a rapid yearly growth in the number of publications regarding nanofluids. There are 30,551 pieces of published research on nanofluids during this timeframe. This graph was plotted using data obtained on (12/2022), from Digital Science's Dimensions platform, available at https://app.dimensions.ai.

Research teams have examined a variety of nanoparticle types, sizes, shapes, and volume fractions [50]–[54]. While the majority of computational research has concentrated on the thermal performance of nanofluids in diverse applications [55]–[57], the majority of experimental studies have focused on improving the thermal conductivity and stability of nanofluids [47], [58]. A lot of research is still being undertaken on nanofluids owing to their many benefits and relative novelty. The next paragraphs discuss a few sources that are pertinent to the ongoing investigations.

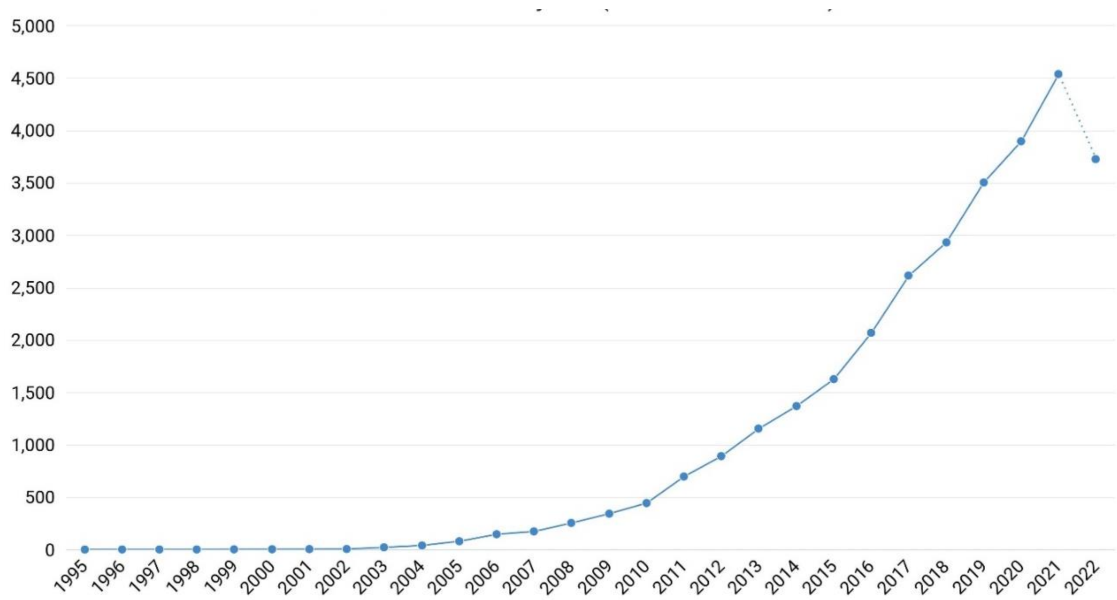



*Figure 13 Number of published research articles on nanofluids between 1995 and 2022.*

This review of the literature examines three distinct topics in the natural convection of nanofluids: the flow and heat transmission of nanofluids in porous media; the behavior of magnetic nanofluids in various magnetic field settings; and the effects of various geometrical parameters on the thermal performance of a nanofluid in a cavity.

### 3.1. Natural convection of nanofluids in a porous media

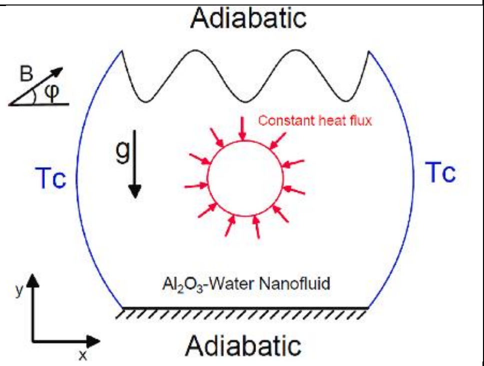
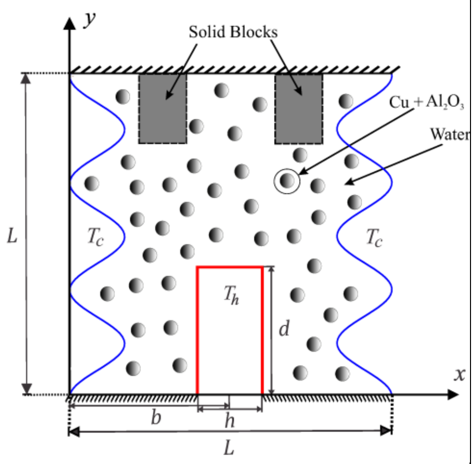
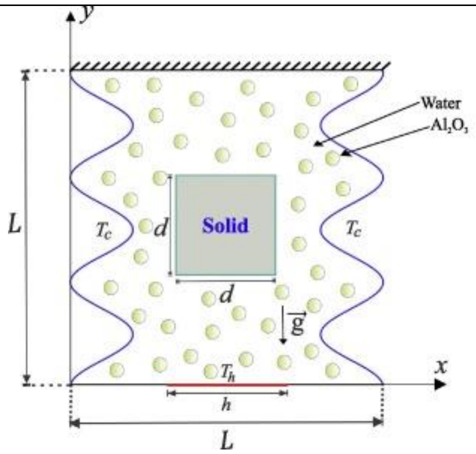
Porous materials are employed as an inexpensive technique to extend the heat transfer area and enhance thermal efficiency. Porous media have been extensively studied in order to enhance heat transmission due to their enormous surface area per unit volume. Recent years have seen a significant increase in research on the natural convective flow of nanofluids across porous surfaces owing to its remarkable potential in a variety of engineering, bio-engineering, and energy systems-related domains [26], [59]. In an oddly shaped container filled with hybrid nanofluids, Ahmed et al. [60] explored how the properties of fluid flow and heat transmission are impacted by the presence of porous media. According to the findings, convection heat transfer predominates in a layer of porous media whereas conduction heat transfer takes over in a layer of non-porous material. In a horizontal, elliptical, porous annulus saturated with nanofluid, Tayebi et al. [61] performed a numerical study of the local thermal non-equilibrium impacts on the free convection features. The findings showed that the LTNE effects improve with the Darcy number, the adjusted thermal conductivity ratio, and the media's porosity. In a hexagon-shaped container with a heated cylinder, Khan et al. [62] addressed the impact of a porous material and an angled magnetic field on the free convection of nanofluid. Their findings show that raising Da improves velocity distributions as well as the rate of heat transfer along the heated cylinder. The boost in flow rates is caused by stronger Da with larger permeability of porous media. Raizah et al. [63] investigated the convective heat transfer patterns of a nanofluid occupying a partial layer of heterogeneous porous media in a V-shaped hollow. The results imply that a rise in the Darcy number improves temperature gradients close to hot areas, increasing the average Nusselt in the process. Tayebi et al.[64] examined the free convection and entropy generation of Cu-Al/water hybrid nanoliquid occupying the space between two elliptical and isothermal cylinders. The findings show that Beavg dramatically decreases with Ra and that this decrease occurs more progressively in the case of absorption, but the insertion of hybrid nanoparticles does not affect Beavg. In a porous container loaded with an Al2O3/water nanofluid, Baghsaz et al.[65] examined the impact of nanoparticle sedimentation on the properties of free convection flow and entropy formation. When compared to the principal streamlines, they discovered that the existence of sediment layers at the bottom of the container lowered the streamlines, which decreased convective heat transfer and rotational flow while enhancing conductive heat transfer. Additionally, they discovered that Ra and Da values had an insignificant influence on the sedimentation time. However, any rise in the Ra or Da levels lengthened the sedimentation period. Tayebi et al.[66] looked into the thermal buoyancy in a horizontal, elliptical annulus filled with a nanofluid and porous media. They claimed that regardless of the values of y and H, the intensity of the natural convective movement in the annulus increased with increasing Da and $\varepsilon$ values of the porous sleeve. Using the two-phase mixing approach, Esfe et al.[67] looked into the natural convection U-shaped cavity loaded with porous media and Al2O3/H2O nanofluid. The results demonstrate that when the heat conductivity increases, Nuavg also rises. It likewise becomes smaller as the Darcy number goes up, from 0 to 60.

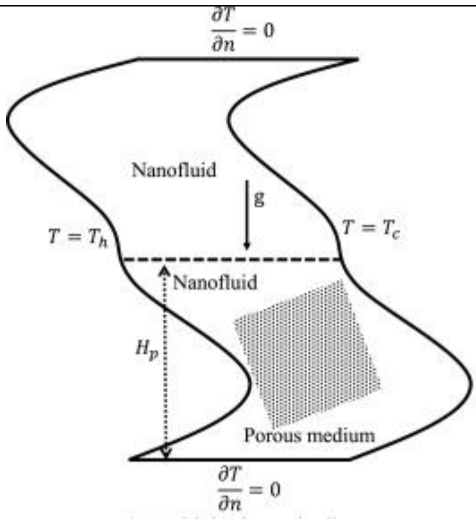
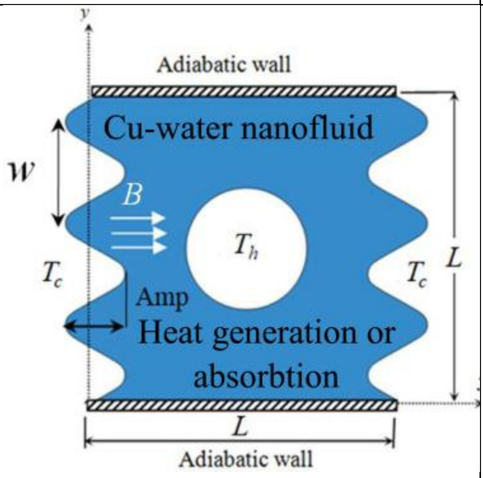
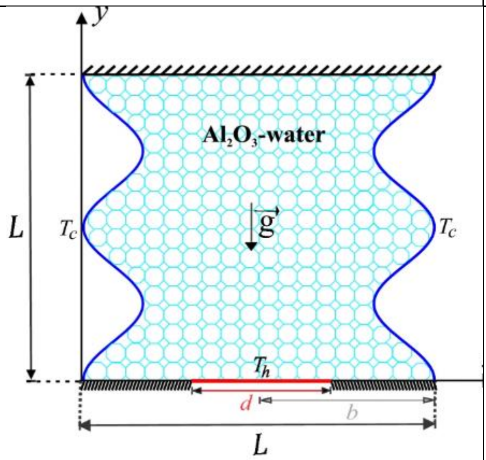
## 3.2. Natural convection of nanofluids in a magnetic field

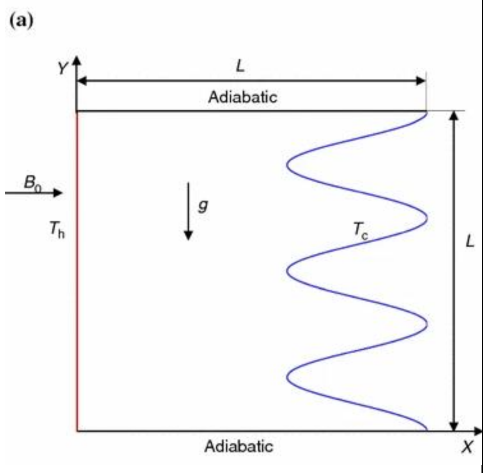
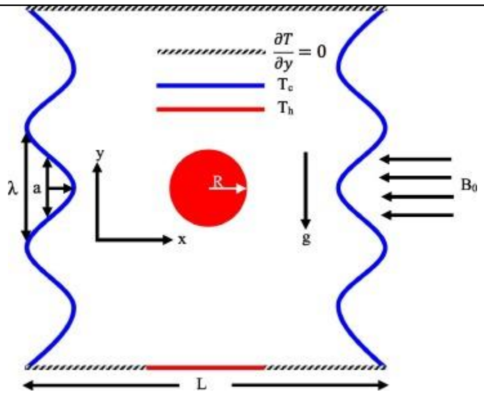
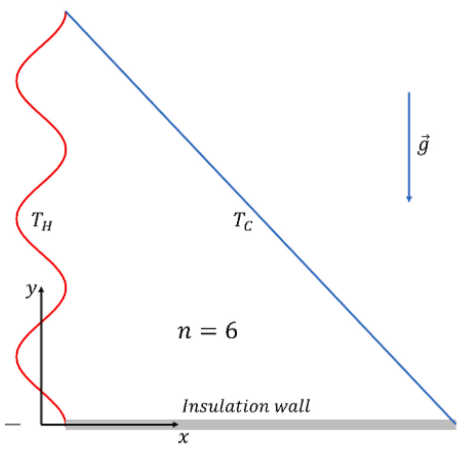
Known as a suspension with strong magnetic characteristics, magnetic nanofluids have electrical conductivity as a key component when using a magnetic field. The ability of magnetic nanofluids to improve and regulate physical characteristics like viscosity, thermal conductivity, and magnetic convection by introducing an external magnetic field is their main advantage over non-magnetic nanofluids [68], [69]. Generally speaking, the major use of magnetic nanofluids is to modify fluid and flow properties for particular objectives. In recent years, there have been two perspectives on the regulation of the fluid by magnetic fields. The first is MHD (Magnetohydrodynamic), which studies a category of fluids having electrical conductivity [70], [71]. Examples of this category of fluids include plasmas, liquid metals, salt water, and nanofluids like iron oxide and copper in water. In order to establish an electric current within a fluid flow or to impart a Lorentz force to a fluid that is carrying an electric current via a magnetic field, MHD offers the necessary circumstances. FHD is the following category (Ferro hydrodynamic). The fluid itself has a Hartmann property in this group. Additionally, several studies have used CFD modeling to examine the MHD natural convection process in nanofluids[72], [73]. Yan et al.[74] explored the cooling of an elliptical nickel permeable material that emits heat and was positioned in the middle of a hollow filled with EG/ Tio2 \sHybrid nanofluid and had vertical cold walls. The findings from this investigation reveal that the growth of the Hartmann number reduced $Nu_{avg}$ in all of the porous Rayleigh numbers and volume fractions besides 9 %. The unsteady MHD free convection flow and heat transfer in an angled U-shaped enclosure saturated with Cu-water nanofluid were examined by Nabwey et al.[75] The findings demonstrate that the mean Nu increases with dimensionless heat source location but decreases with heat source length and Hartmann number. Steady heat flux was taken into consideration when Abderrahmane et al.[76] explored the MHD convective flow of non-Newtonian nanoliquid within a halved porous annulus enclosure. The results show that for various Rayleigh numbers, the cavity's inclination angle and the Hartmann number may be regarded as useful control parameters. The velocity field slowed down when the magnetic field was applied, which led to lower convection heat transfer and Nusselt number.Rahman et al.[77] investigated how an angled magnetic field affected a nanofluid with a non-Newtonian flow in a rectangular area. According to the research, the average Nusselt number increases with the increase in magnetic angle up to an angle of 90° before it begins to worsen at 120°. Cao et al.[78] examined the impact of thermophoresis motion and Brownian on The MHD natural convection of water-based Cu nanofluid inside a square heat exchanger container with two cylinders on the left and right sides as cooler and heater, respectively. Their findings indicated that the nanoparticle transport zone was expanded by the introduction of a magnetic field. In a cubical enclosure filled with a hybrid water nanofluid, Boulahia et al.[79] analyzed the irreversibility of the MHD free convection. The outcomes showed that increasing the Hartmann value from 15 to 45 causes the rate of heat transfer to diminish. The magnetic field's inclination angle gradually increasing also aids in enhancing the heat transfer rate. Within a complex-shaped container with a roughly circular heater, Chammam et al.[80] examined the magnetic natural convection of water-based $Fe_3O_4$ nanoliquid. The results show that applying a magnetic field may reduce the intensity of natural convection and the pace of heat transfer inside the system, making it a useful regulating factor in heat transfer applications. Boulahia et al.[81] reported investigation of the entropy production originating from MHD free convection inside a perforated cavity containing nanofluid and a heated object located at the center. From the findings, it is evident that the influence of the number N of undulations becomes gradually inconsequential with the growth in the magnetic field Ha. In a square-shaped container subjected to a horizontal periodic magnetic field, Islam et al.[82] explored the unsteady free convective heat transfer of various nanofluids. In comparison to other kinds of nanofluids, the $Fe_3O_4$-water nanofluid exhibits the highest heat transfer capability, according to the data. The rate of heat transfer increases when more nanoparticles are added to the base fluid, however it diminishes as the Hartmann number and diameter of the particles rise. Under MHD effects, Al-Farhany et al.[83] explored natural convective heat transmission in a U-shaped container packed with a nanofluid/saturated porous medium and two baffles. The findings are significant, demonstrating that raising the values of Ra, Da, and the volume percentage of nanoparticles improves heat transmission. The Hartmann number, on the other hand, has an opposite effect on heat transfer increment.

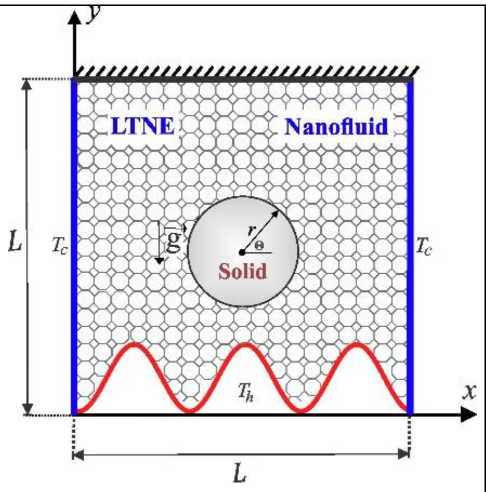
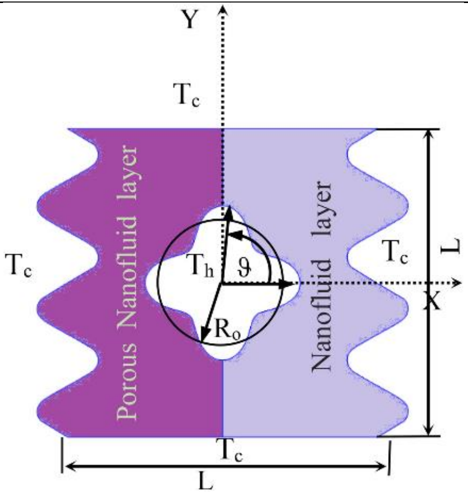
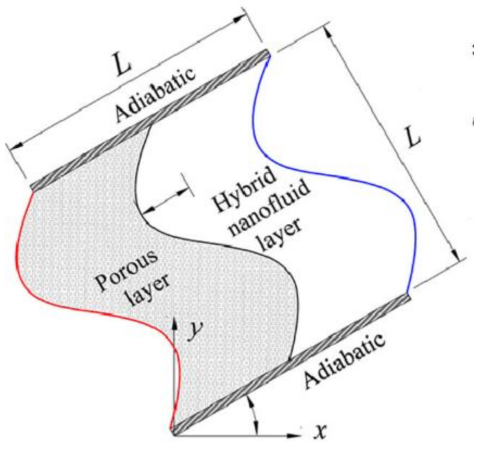
The natural convection of nanofluid in squre enclosure with side walls have been experimentally and numerically investigated [84-114]. A brief summary of theses investigations is presented in Table 1

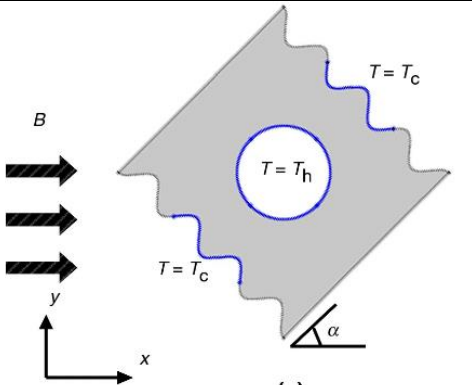
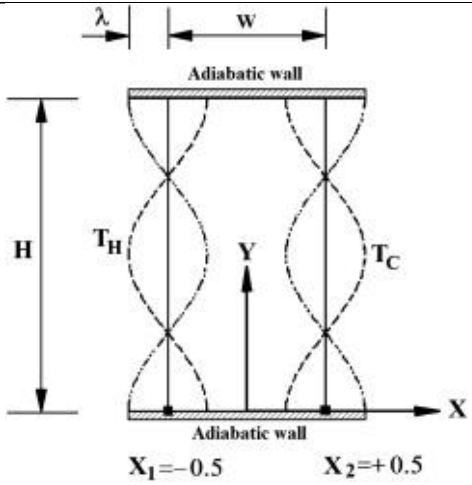
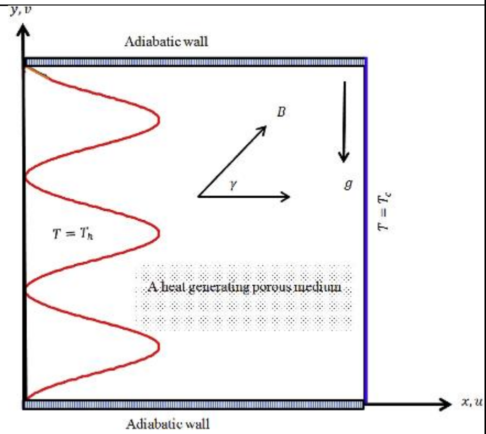
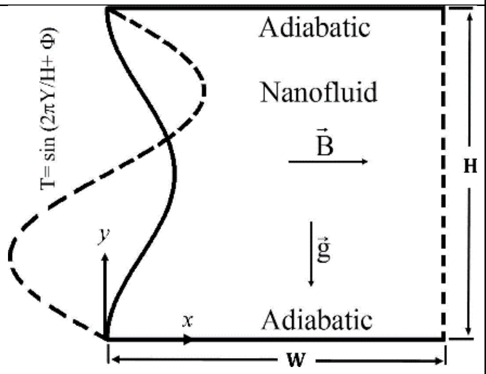
*Table 1 Summary of experimental and numerical studies on natural convection of nanofluids.*

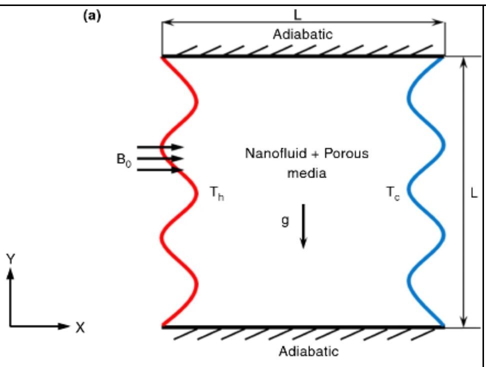
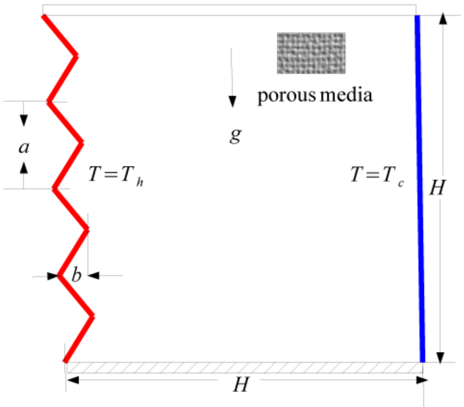
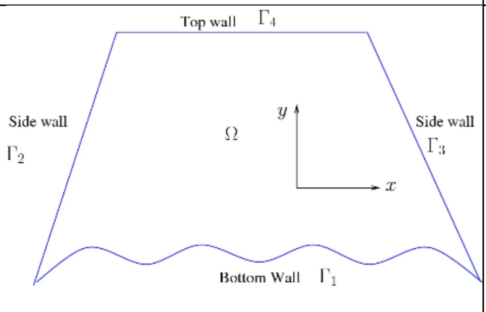
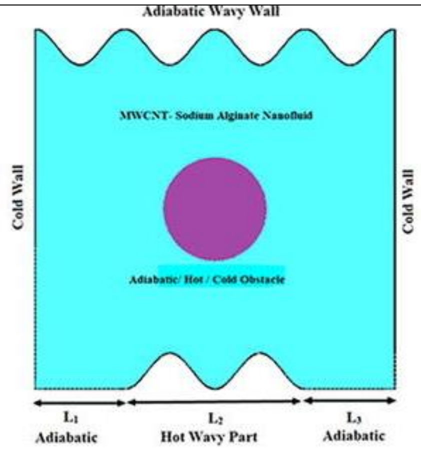
| Authors | Enclosure geometry | Nanofluid | Observations |
|---|---|---|---|
| Dogonchi et al. [84] |  | $Al_2O_3/H_2O$ | The $Nu_{avg}$ is unaffected by changes in the magnetic field's orientation. Entropy production rises as cavity curvature grows. |
| Alsabery et al. [85] |  | Cu-$Al_2O_3$ / $H_2O$ Hybrid nanofluid | Comparing hybrid nanofluids to basic nanofluids, the Nusselt number is improved. Such amplification is particularly pronounced for low Rayleigh numbers. |
| Hashim et al. [86] |  | $Al_2O_3/H_2O$ two-phase model | By adding nanoparticles and choosing an ideal number of oscillations, the heat transmission within the cavity is improved. |

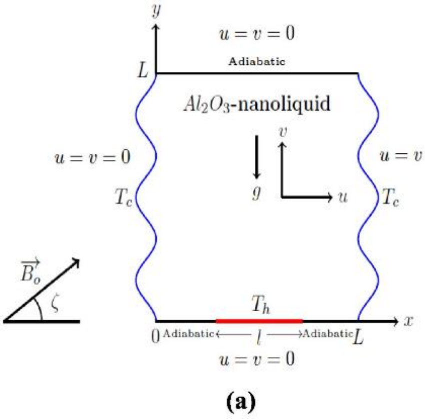
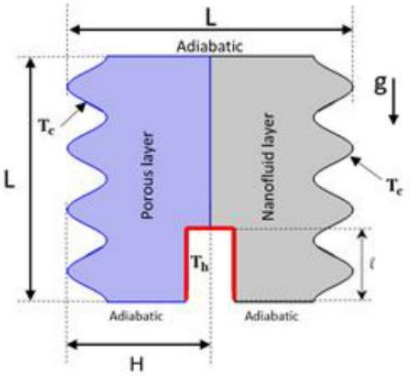
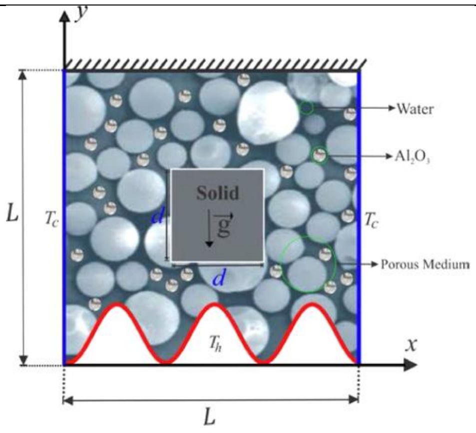
| | | | |
|---|---|---|---|
| Abdelraheem et al. [87] |  | Cu/$H_2O$ non-Darcy porous model | Higher values of the Darcy parameter Da≤$10^{-3}$ (lower porous resistance) lead to the penetration of fluid flows into the porous medium layer, and this penetration grows as the Rayleigh number rises. |
| Abdulkadhim et al. [88] |  | Cu/$H_2O$ | Raising Ha has a minor influence on Nusselt number for low Ra, whereas, it dramatically drags Nu down up to 33 percent for higher Ra, due to constraining convection. |
| Alsabery et al. [89] |  | $Al_2O_3$/$H_2O$ non-Darcian porous model | The heater length, its location, and the nanoparticles concentration walls as well as the wave number on the side vertical may be the control parameters for natural convective flow and heat transmission inside the wavy cavity. |

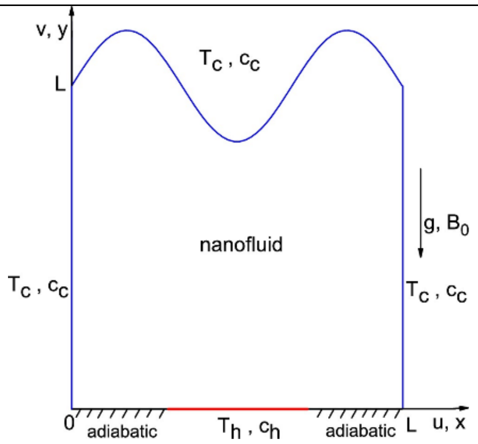
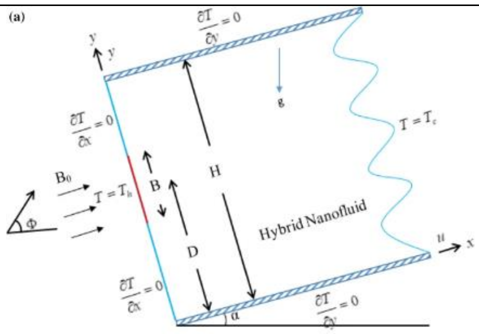
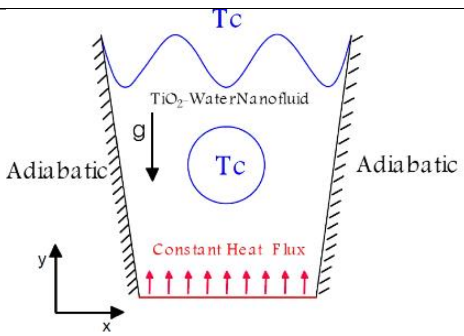
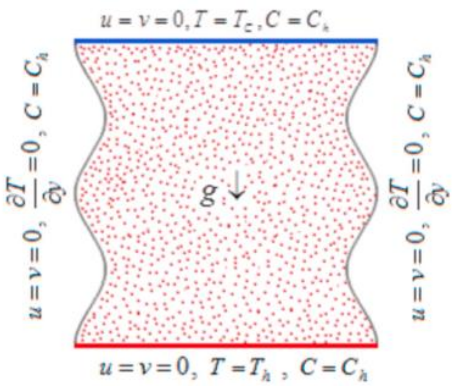
| | | | |
|---|---|---|---|
| Dogonchi et al. [90] |  | Cu/$H_2O$ | For Ra = $10^3$ and $10^4$, the average Nusselt number rises with the rising undulation number and wavy contraction ratio.<br>The intensity of the convective flow rises with the increase of Ra number and it declines with the increase of the Hartmann number. |
| Mohammad et al.<br>[91] |  | Cu-$Al_2O_3$/<br>$H_2O$<br>hybrid<br>nanofluid | The intensity of fluid motion gets larger for a wavy cavity having a heat-producing impediment compared to a plain cavity without obstruction.<br>The heat transmission rate also rises with the roughness of the cavity. |
| Shekaramiz et al.<br>[92] |  | $Fe_3O_4$/ $H_2O$ | The tilt of the magnetic field doesn't alter nanofluid dispersion within the container.<br>The Nusselt number is inversely linked to the undulation number.<br>Entropy generation initially rises and then stays constant with increasing Ha. |

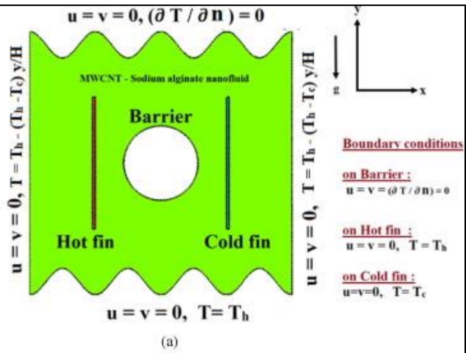
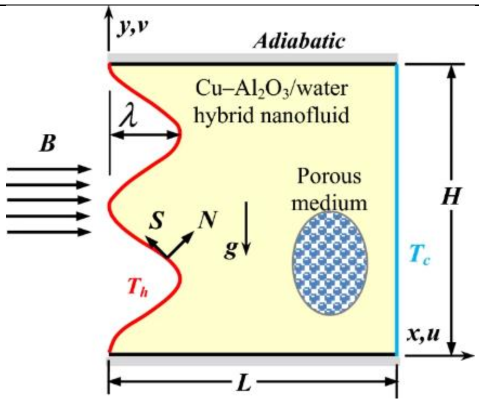
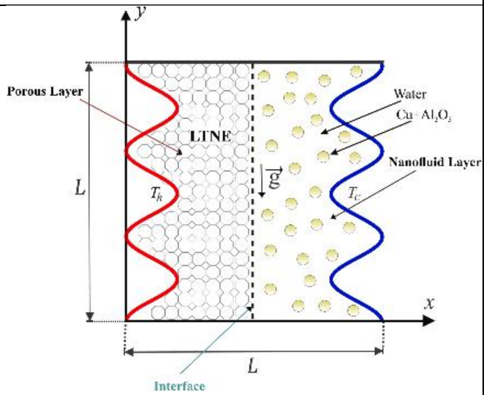
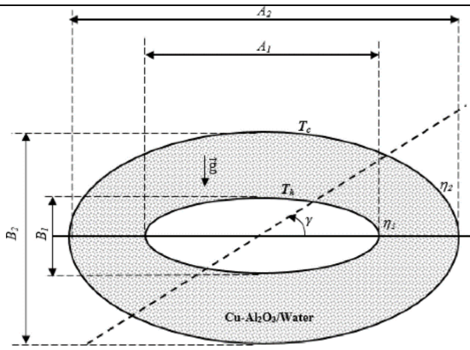
| | | | |
|---|---|---|---|
| Alsabery et al. [93] |  | $Al_2O_3$/ $H_2O$ | When taking into account high porosity values, the average Nusselt number rises with the addition of ϕ, but for low porosity values, the average Nusselt number falls after peaking.<br>The use of nanoparticles is at its best when the undulations are small. |
| Abdulkadhim et al.<br><br>[94] |  | Ag/ $H_2O$ | The average heat transmission is decreased when the porous layer's thickness is increased.<br>At N = 4, as the inner sinusoidal cylinder moves downward vertically, the maximum fluid flow strength develops. |
| Kadhim et al. [95] |  | Cu-$Al_2O_3$/<br><br>$H_2O$<br><br>hybrid<br><br>nanofluid | A comparison of the increase of heat transfer using Al2O3 nanoparticle suspension in water as a single nanofluid and utilizing Cu-Al2O3 nanoparticle suspension in water as a hybrid nanofluid shows that the hybrid nanofluid performs better in terms of heat transfer.<br>The primary convective cells and the isotherms' shapes are influenced by the wavenumber of the wavy wall. |

<table>
<tr>
<td>Gupta et al. [96]</td>
<td>
</td>
<td>$Cu-Al_2O_3/$<br>$H_2O$<br>hybrid<br>nanofluid</td>
<td>The overall heat transfer pattern is zigzag with increasing waviness (undulation parameter).<br>The average Nusselt number exhibits an opposing trend with a large concentration of hybrid nanoparticles when the Rayleigh number is high ($Ra>10^5$).</td>
</tr>
<tr>
<td>Esmaeil et al. [97]</td>
<td>
</td>
<td>$Cu/H_2O$</td>
<td>The average Nusselt value lowers with increasing surface waviness and grows with increasing Grashof number.<br><br>With rising Grashof number and decreasing surface waviness, the creation of entropy rises.</td>
</tr>
<tr>
<td>Ahmed et al. [98]</td>
<td>
</td>
<td>Not stated</td>
<td>Both the undulation number and the wavy contraction ratio have an increasing relationship with the rate of heat transfer.</td>
</tr>
<tr>
<td>Ashorynejad et al.<br><br>[99]</td>
<td>
</td>
<td>$Cu-Al_2O_3/$<br>$H_2O$<br>hybrid<br>nanofluid</td>
<td>The rise in phase deviation has a beneficial effect on improving heat transfer at higher Ra.<br>The Nusselt number is inversely linked to the Hartmann number that decreases, but it grows as Ra and the volume fraction of nanoparticles rise.</td>
</tr>
</table>

| | | | |
|---|---|---|---|
| Hamzah et al. [100] |   | Cu-$Al_2O_3$/ $H_2O$ hybrid nanofluid | The Darcy number and surface waviness both significantly affect the suppression of heat transport. The effect of Ha becomes negligible and may be disregarded for $Da < 10^{-3}$. |
| Chamkha et al. [101] |   | Cu/ $H_2O$ | The local and averaged heat transfer rates decline with increasing triangle wave corrugation frequency, which is more efficient for larger Darcy and Grashof numbers. |
| Reddy et al. [102] |   | $Al_2O_3$/ $H_2O$ | In a high Hartmann number flow, the sensitivity of the Nusselt number to the Casson parameter and the solid volume percentage is noticeable. |
| Ganesh et al. [103] |   | Casson-based MWCNT nanofluid | The Casson parameter, radiation parameter, MWCNT volume percentage, and Rayleigh number all led to a rise in the mean Nusselt number along the heated wavy wall for all forms of obstacles. |

| | | | |
|---|---|---|---|
| Sivaraj et al. [104] |   | $Al_2O_3$/ $H_2O$ | Convective heat transfer rate and average entropy generation intensity decrease as the undulation number or Hartmann number increases. |
| Bendrer et al. [105] |   | $Fe_3O_4$-MWCNT/ $H_2O$ hybrid nanofluid | When the Rayleigh number increases, the efficiency of heat transfer and nanoliquid flow is significantly improved. The low values of the Ra are characterized by a predominance of the irreversibility of heat transport. When Ha is increased from 0 to 100, an 84.78%.reduction in values of the maximum absolute value of the stream function is observed. |
| Alsabery et al. [106] |   | $Al_2O_3$/ $H_2O$ | Entropy is generated within the container primarily as a result of thermal irreversibility at lower Darcy number and porosity levels as well as at greater numbers of undulations and nanoparticle volume fractions. |

| | | | |
|---|---|---|---|
| Parveen et al. [107] |  | $Al_2O_3$/ $H_2O$ | The rate of heat and mass transfer increases as the Rayleigh number and volume percentage of nanoparticles rise, however it is observed that these rates fall when the Hartmann number and buoyancy ratio rise. |
| Shaik et al. [108] |  | $TiO_2$–Cu/<br><br>$H_2O$<br><br>hybrid<br><br>nanofluid | As the undulation parameter rises, the local Nusselt variation diminishes.<br><br>The magnetic field has a strong influence on the flow pattern within the cavity, and the fluid velocity flows clockwise into the wavy surface as a result of the magnetic field imposed in the inclination direction. |
| Fereidooni et al.<br><br>[109] |  | $TiO_2$/ $H_2O$ | If the amplitude of the wavy wall rises from 0.05 to 0.1, Nuavg drops by 31%. Whereas, Ra going from $10^3$ to $10^5$ causes Nuavg to rise by up to 36%. |
| Uddin et al. [110] |  | CuO/ $H_2O$ | When the wave number is increased to 2, heat transmission is decreased by 16.98%, and when it is raised to 4, it is enhanced by 3.62%. |

| | | | |
|---|---|---|---|
| Ganesh et al. [111] |  | MWCNT–<br>Casson<br>nanofluid | Rising Rayleigh number, Casson parameter, the amplitude of waviness, and solid volume percentage of MWCNT all contributed to a 257 %, 189 %, 116%, and 30% increment in the rate of heat transmission, respectively. |
| Mandal et al. [112] |  | $Cu\text{-}Al_2O_3$/<br>$H_2O$<br>hybrid<br>nanofluid | Heat transmission and flow intensity both rise as the Ra becomes higher. However, as Da and Ha rise, they decline. |
| Alsabery et al.<br>[113] |  | $Cu\text{-}Al_2O_3$/<br>$H_2O$<br>hybrid<br>nanofluid | The liquid Nusselt number increases by 17% as nanoparticle concentration increases from 0 to 0.04. In comparison to basic nanofluids, the hybrid nanofluid exhibits a superior improvement in heat transmission.<br>The value of Da determines how the amplitude A of the wall undulations impacts the flow and heat transfer. When Da is low, utilizing a cavity with a larger value of A improves heat transmission; when Da is high, the opposite is true. |
| Tayebi et al. [114] |  | $Cu\text{-}Al_2O_3$/<br>$H_2O$<br>hybrid<br>nanofluid | The natural convective flow, the rate of heat transfer, and both thermal and frictional entropy formation inside the annulus are all increased when the Rayleigh number is increased or when hybrid nanoparticles are used in pure water. |

# 4. Conclusion

In this chapter, a brief definition of convective heat transfer, magnetohydrodynamic, porous media, and nanofluids have been comprehensively discussed. A synthesis of the various works relating to these subjects has been carried out to clarify and understand the characteristics of the flow, the heat transfer and the problems related to the evacuation of heat using natural convection. It has been shown that research in the field of heat transfer by the use of nanofluids is booming and it is in this context that we have devoted this work on the numerical study of heat transfer by natural convection in a cavity filled with different nanofluids.

# Chapter II: Mathematical model and Simulation

# Mathematical model and Simulation

## 1. Introduction

This chapter presents the governing equations that describe mathematically the nanofluid flow under the effect of a magnetic field and porous media, the equations of Navier-Stokes, as well as the nanofluid's thermo-physical proprieties correlations and the non-dimensional numbers related to this study. Furthermore, the chapter discusses numerical solution procedures via the commercial CFD code COMSOL. Finally, the computational domain's shape, mesh, and validation procedure are described.

## 2. Numerical solution procedure

Both theoretical and experimental methods may be used to analyze flow and heat transport in thermodynamics. In the study of thermodynamics, experimental research on such a subject has not been particularly well-liked due to its restricted flexibility and applicability. It is undesirable from both a time and cost perspective to investigate each change in geometry and boundary conditions, which necessitates unique experimental requirements and arrangements. On the other hand, the theoretical examination may be conducted using either an analytical technique or a numerical one. The analytical approaches to problem-solving are not very helpful in resolving real issues. This is mostly because there are many variables at play, complicated geometrical bodies and boundary constraints, and arbitrary border forms. . Therefore, the only other options for solving issues of practical importance are numerical approaches.

The governing equations in heat transfer and fluid dynamics contain conservation versions of the Navier-Stokes equations written in terms of surface integral equations or the control volume. To depict these thermal fluid flow situations, an approximate numerical solution is required, which may be generated using the CFD (Computational Fluid Dynamics) algorithm. The partial differential equations of heat transport and fluid dynamics s are discretized in order to generate a system of approximating algebraic equations, which then may be solved using a computer. The approximations are applied to limited domains in space and/ or time so the numerical solution offers results at selected points in space and time. In order to do CFD computation, a set of numbers that closely matches a real-world system must be created. The results of the computing process help us better understand how a system behaves. Numerous discritization strategies can be employed for the numerical simulation in CFD

- Finite element method (FEM)
- Finite volume method (FVM)
- Finite difference method (FDM)
- Boundary volume method (BVM)
- Boundary element method (BEM)

The numerical simulation conducted in this thesis is done using the Galerkin finite element method (FEM).

## 2.1. Finite element method

A grasp of the finite element approach is required to operate the simulation software utilized in this thesis since it is a finite element solver. The detailed intricacies of the program's finite element approach would need a lengthy explanation, but this section offers a succinct overview of what it is.

The most basic description of the finite element method is a methodology for calculating a numerical solution to a boundary value issue given by a differential equation. The differential equation itself is utilized to explain any area of engineering, for this project, incompressible fluid flow. Additional boundary conditions dictate what the solutions to those equations have to be on the border of the form in consideration. In order to numerically solve the issue, the geometry in which the equation will be solved must be divided into a stiffness matrix which is a collection of points inside the bounds of the geometry. The equations will be addressed on each of these distinct points. Once the points are established in position, they are linked to one another. For a two-dimensional region, these interconnections sometimes create rectangular mesh elements, other times they produce triangular mesh components. What gives the "mesh" its apparent mesh-like appearance are these points and the links that connect them. Thus, in order to approximate a continuous function, the finite element approach solves it at discrete places.

Accurate and precise simulation of heat transfer and flow dynamics within complicated geometry is of considerable relevance to fulfill the severe demand for better efficiency as well as an economic challenge. It is recognized that these complicated geometries appear most commonly in CFD. The grid indexing is straightforward but certain complications occur for the domain with a complicated shape. For the finite element approach, there are no limits on the connection of the elements when the faces of the elements are appropriately oriented and have similar nodes for the surrounding elements. This versatility enables us to represent a highly complicated shape. Although, the existence of complex structures slows down the computational algorithms.

The current study highlights the use of finite element methods to tackle flow and heat transfer issues. The specifics of this approach are detailed in the next section.

The computational process employed in the construction of solutions for the current problems is based on Galerkin finite element method.

The primary stages involved in Galerkin finite element modeling of a typical problem are:

- Discretization of the domain into a collection of finite elements (mesh generation).
- Weighted-integral or weak formulation of the differential equation to be studied.
- Construction of the finite element model of the issue utilizing its weighted-integral or weak version.
- Assembly of finite components to generate the global system of algebraic equations.

- Establishing boundary conditions
- Equations are solved numerically
- Post-processing of the solution and relevant Data.

## 2.2. Boussinesq approximation

Convection flow's governing equations are linked to elliptic partial differential equations, which adds to their complexity. These equations' partial, elliptic structure and the inescapable fluctuation of density with temperature or concentration provide the biggest obstacles to finding a solution. These equations are often greatly simplified by using a number of approximations. Among these, the 1903 Boussinesq approximation is taken into consideration here [115].

The fluid characteristics in flows accompanied by heat transfer are typically functions of temperature. Although the changes could be slight, they nonetheless drive the fluid motion.

So the density is expressed as the sum of a refrence density $\rho_0$ and a fluctuation $\Delta\rho$

$$\rho = \rho_0 + \Delta\rho \tag{2.1}$$

In the Boussinesq approximation, if the variations in density are minimal, the density may be regarded as constant in the unsteady and convection terms, while in the gravitational term it may be treated as a variable.

## 2.3. COMSOL

A finite element application called COMSOL was employed in this research. Pre-processor, mesh generator, processor (or solver), and post-processor are all included in Comsol as single software. COMSOL also includes additional useful features such as optimization tools and an application builder. The pre-processor part of COMSOL consists of a 3D computer-aided design (CAD) program that can be linked to solid works, and a model builder for the application of boundary conditions for fluid dynamics and heat transfer, such as velocity or temperature conditions.

Additionally, the materials' characteristics are specified as well, and COMSOL has a library where the properties of common materials are recorded and available for customization.

The model is divided into elements by the mesh generator, which are geometric bodies that determine the material characteristics of a portion of the system. Nodal positions determine the element geometry. These elements may be adjusted in size, shape, or level of refinement. In order to solve the stated model, COMSOL's processor section comprises equations for heat transfer, fluid flow, and solid property. There are three primary types of non-linear solvers available in the COMSOL application that may be utilized for this. The tolerance of convergence needed to find a solution may be changed, as can the sequence in which the equations are solved by the solver. These changes can also affect how the solver generates a solution.

## 2.4. Dimensionless parameters

The dimensionless parameters may be seen as measurements of the relative significance of various flow-related characteristics. Below is a discussion of several dimensionless variables relevant to our study:

### 2.4.1. Grashof number Gr

The dimensionless Grashof number, which measures the ratio of the buoyancy force to the viscous forces applied to the fluid, determines the flow regime in free convection and is described as:

$$Gr = \frac{g\beta L^3\left(T_w - T_\infty\right)}{v^2} \tag{2.2}$$

Where g is gravitational acceleration due to Earth, β is the coefficient of thermal expansion, Tw is the surface temperature, T∞ is the bulk temperature, L is the vertical length, and ν is the kinematic viscosity.

In free convection, the Grashof number serves the same purpose that the Reynolds number does. As a result, the Grashof number serves as the primary criteria for identifying whether the fluid flow in free convection is laminar or turbulent. A value below $10^8$ indicates that the flow is laminar, while a value above $10^9$ indicates that the flow is turbulent.

### 2.4.2. Prandtl Number Pr

The dimensionless parameter Prandtl number, which is defined as Pr = Molecular diffusivity of momentum / Molecular diffusivity of heat, provides the best description of the relative thickness of the velocity and thermal boundary layers. The number bears Ludwig Prandtl's name, who developed the boundary layer theory and established the idea of a boundary layer in 1904 [116].

### 2.4.3. Nusselt Number Nu

The Nusselt number measures the increase of heat transmission across a fluid layer as a consequence of convection compared to conduction through the same fluid layer and is described as:

$$Nu = hL / k \tag{2.3}$$

where h is the convective heat transfer coefficient of the flow, L is the characteristic length, and k is the thermal conductivity of the fluid.

The Nusselt number is named after Wilhelm Nusselt, who made significant contributions to convective heat transfer in the first half of the twentieth century, and it is viewed as the dimensionless convection heat transfer coefficient. The larger Nusselt number indicates a large temperature gradient at the surface and hence, high heat transfer by convection. A Nusselt number of Nu = 1, for a fluid layer, represents heat transfer across the layer by pure conduction.

### 2.4.4. Rayleigh Number Ra

The Rayleigh number (Ra) is a dimensionless number associated with the buoyancy-driven flow. When the Rayleigh number is less than a critical value for that fluid, heat transmission is mostly conduction; when it is greater than the critical value, heat transfer is largely by convection. In 1926, Jeffreys first determined the critical Rayleigh number for the case of infinite parallel plates, Ra=1708. The Grashof number, which defines the link between buoyancy and viscosity inside a fluid, and the Prandtl number, which describes the relationship between momentum diffusivity and thermal diffusivity, are combined to form the Rayleigh number, which bears Lord Rayleigh's name. As a result, the Rayleigh number itself may be understood as the product of the buoyancy and viscosity force ratios and the momentum/thermal diffusivity ratio.

$$Ra = \frac{g\beta \Delta T L^3}{\nu a} \tag{2.4}$$

Where g is acceleration due to gravity, β is the thermal expansion coefficient, ν is the kinematic viscosity., α is the thermal diffusivity, and $\Delta T$ temperature gradient.

### 2.4.5. Hartmann number

Julius Hartmann was the first to define the Hartmann number (Ha) as the relationship between electromagnetic force and viscous force [117]. In fluid flows across magnetic fields, this number is commonly measured. Its definition is:

$$\text{Ha} = BL\sqrt{\frac{\sigma}{\mu}} \tag{2.5}$$

Where B is the magnetic field intensity, L is the characteristic length scale, σ is the electrical conductivity, and μ is the dynamic viscosity

### 2.4.6. Darcy number

The Darcy number (Da) in fluid dynamics via porous media reflects the relationship between the permeability of the medium and its cross-sectional area, which is typically the diameter squared. The quantity, which bears Henry Darcy's name, is established by non dimensionalizing Darcy's Law's differential form.

$$Da = \frac{K}{L^2} \tag{2.6}$$

Where K is the permeability of the medium, and d is the characteristic length.

## 2.5. Governing equations

Despite being solid-liquid mixes, nanofluids are often treated as a single-phase (homogenous) fluid in most investigations of natural convection. In reality, the particles are expected to travel at the same speed as the fluid because of the extreme size and low concentration of the suspended nanoparticles. Additionally, the solid particle-liquid combination may be roughly thought of to behave as a typical single-phase fluid with characteristics that are to be compared to those of the components by taking into account the local thermal equilibrium. The density, specific heat, thermal conductivity, and viscosity in the governing equations for a homogeneous study of natural convection are modified values of continuity, momentum, and energy.

The differential equations representing mass, momentum, and energy conservation govern natural convection. The current flow is thought to be two-dimensional, laminar, stable, and incompressible. A uniform magnetic field of constant magnitude and the horizontal direction is applied to the current flow. In the energy equation, the viscous dissipation element is ignored. For the nanofluid characteristics, the Boussinesq approximation is used to connect density changes to temperature changes and couple the temperature field and flow field. We assume that the base fluid and the nanoparticles are in thermal equilibrium and that there is no slippage between them. Cartesian coordinates are considered for the Navier-Stokes equations. The following are the governing equations (Navier–Stokes equations) for 2D steady natural convection flow of nanofluid under a magnetic field:

Mass Conservation Equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.7}$$

Momentum Conservation Equations:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2.8}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}}g\left(T-T_c\right)-\frac{\sigma_{nf}B_0^2 v}{\rho_{nf}} \tag{2.9}$$

Energy Conservation Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{2.10}$$

If the nanofluid is flowing through a porous media

Mass Conservation Equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2.11}$$

Momentum Conservation Equations:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\mu_{nf}}{\rho_{nf}K}u \tag{2.12}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\frac{\mu_{nf}}{\rho_{nf}}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{\beta_{nf}}{\rho_{nf}}g\left(T-T_c\right)-\frac{\sigma_{nf}B_0^2 v}{\rho_{nf}}-\frac{\mu_{nf}}{\rho_{nf}K}v \tag{2.137}$$

Energy Conservation Equation:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{2.14}$$

The properties of the nanofluid are calculated as follows:

We note that φ is the solid volume fraction.

A simple rule of mixtures may be used to calculate the density of the nanofluid.

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s \tag{2.15}$$

$(\rho Cp)_{nf}$ is defined as a single quantity $\chi_{nf} = (\rho Cp)_{nf}$, and then a parallel mixture rule is used

$$\chi_{nf} = \varphi(\rho Cp)_s + (1-\varphi)(\rho Cp)_f \tag{2.16}$$

hence the specific heat capacity may be determined as

$$(Cp)_{nf} = \frac{\chi_{nf}}{\rho_{nf}} = \frac{(1-\varphi)(\rho Cp)_f + \varphi(\rho Cp)_s}{(1-\varphi)\rho_f + \varphi\rho_s} \tag{2.17}$$

The thermal expansion coefficient of the nanofluid is evaluated as follows

$$\beta_{nf} = (1-\varphi)\beta_f + \varphi\beta_s \tag{2.18}$$

The thermal diffusivity of the nanofluid is evaluated as follows

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}} \tag{2.198}$$

The electrical conductivity of the nanofluid is evaluated as follows

$$\sigma_{nf} = (1-\varphi)\sigma_f + \varphi\sigma_s \tag{2.20}$$

$k_{nf}$ is the effective thermal conductivity of the nanofluid and it is determined by using the Maxwell model as follows [118]:

$$k_{nf} = k_f \frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + \varphi(k_f - k_s)} \tag{2.21}$$

The effective dynamic viscosity of the nanofluid is calculated according to the Brinkman model as follows [119]:

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \tag{2.22}$$

If the nanofluid is a hybrid nanofluid then the flowing expressions are used to calculate the properties of the solid phase of the nanofluid (nanoparticles).

We consider the hybrid nanofluid including nanoparticles (np1) and nanoparticles (np2)

$$\varphi_s = \varphi_{np1} + \varphi_{np2} \tag{2.23}$$

$$\rho_s = \frac{\varphi_{np1}\rho_{np1} + \varphi_{np2}\rho_{np2}}{\varphi} \tag{2.24}$$

$$(Cp)_s = \frac{\varphi_{np1}(Cp)_{np1} + \varphi_{np2}(Cp)_{np2}}{\varphi} \tag{2.25}$$

$$\beta_s = \frac{\varphi_{np1}\beta_{np1} + \varphi_{np2}\beta_{np2}}{\varphi} \tag{2.26}$$

$$k_s = \frac{\varphi_{np1}k_{np1} + \varphi_{np2}k_{np2}}{\varphi} \tag{2.27}$$

$$\sigma_s = \frac{\varphi_{np1}\sigma_{np1} + \varphi_{np2}\sigma_{np2}}{\varphi} \tag{2.28}$$

We performed numerical simulations of Newtonian hybrid nanofluid ($Fe_3O_4$- MWCNT (50-50%) /$H_2O$) natural convection flow in a porous enclosure. The thermophysical characteristics of water (base fluid) and spherical $Fe_3O_4$ and MWCNT nanoparticles with a diameter of 50 nm are presented in Table 2.

*Table 2 thermo-physical characteristics of the nanoparticles and fluid (Fe3O4- MWCNT / water (50/50).*

| | **$\rho$ (kg/m$^3$)** | **$C_p$ (J/kg k)** | **k(W/m k)** | **σ(S/ m)** | **β (K $^{-1}$ )** |
|---|---|---|---|---|---|
| **Pure water ($H_2O$)** | 997.1 | 4179 | 0.613 | $5.5\times10^{-6}$ | $21\times10^{-5}$ |
| **$Fe_3O_4$** | 5810 | 670 | 6 | $2.5\times10^{-4}$ | $1.3\times10^{-5}$ |
| **MWCNT** | 2100 | 711 | 3000 | $1.9\times10^{-4}$ | $4.2\times10$ |

The Dimensionless number presented in section 2.4 and the following specifications have been considered in order to reconstruct the equations in a dimensionless form:

$$X=\frac{x}{L};Y=\frac{y}{L};U=\frac{uL}{\alpha_f};V=\frac{vL}{\alpha_f};P=\frac{pL^2}{\rho_{nf}\alpha_f^2};\theta=\frac{T-T_c}{T_H-T_c};.$$

The dimensionless forms of the governing equations are:

Mass Conservation Equation:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (2.29)$$

Momentum Conservation Equations:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}\Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \qquad (2.30)$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)$$
$$+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}Ra\Pr\theta-\frac{\rho_f}{\rho_{nf}}Ha^2\Pr V \qquad (2.31)$$

Energy Conservation Equation:

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\frac{\alpha_{nf}}{\alpha_f}\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right) \quad (2.32)$$

As for the flow in porous media

Mass Conservation Equation:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (2.33)$$

Momentum Conservation Equations:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}\Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)-\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}\frac{\Pr}{Da}U \quad (2.349)$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}Ra\Pr\theta-\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}\frac{\Pr}{Da}V-\frac{\rho_f}{\rho_{nf}\left(1-\varphi\right)^{2.5}}Ha^2\Pr V \quad (2.35)$$

Energy Conservation Equation:

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\frac{\alpha_{nf}}{\alpha_f}\left(\frac{\partial^2\theta}{\partial X^2}+\frac{\partial^2\theta}{\partial Y^2}\right) \quad (2.36)$$

# 3. Presentation of the results

The results of our numerical simulations for flow fields and thermal fields are visualized graphically by the contours of the current function (streamlines) and isotherms, respectively.

## 3.1. Streamlines

The structure of the flow is visualized using the current function "ψ".

For the considered enclosures, the flow pattern was expressed by streamlines that are estimated by the mathematical model:

$$\frac{\partial^2\psi}{\partial X^2}+\frac{\partial^2\psi}{\partial Y^2}=\frac{\partial U}{\partial Y}-\frac{\partial V}{\partial X} \quad (2.36)$$

## 3.2. Isotherms

An isotherm is a line of constant temperature.

## 3.3. Average Nusselt number ($Nu_{avg}$)

$Nu_{avg}$ along the hot walls of the cavity is considered to evaluate the overall heat transfer rate and is defined as:

$$Nu_{avg}=\int_0^1 Nu_{loc}dY\bigg|_{X=0} \quad (2.37)$$

where symbol n is the normal direction to the surface, and:

$$Nu_{loc}=-\frac{k_{nf}}{k_f}\frac{\partial\theta}{\partial n}\Bigg\}_{wall} \quad (2.38)$$

## 3.4. Entropy

Due to the coupled magnetohydrodynamic processes, the physical system under investigation incurs irreversibilities. The entropy created by this process is formed by three components:

irreversibility due to local temperature gradients; the influence of viscous dissipation; and the presence of a magnetic field.

According to linear transport theory's local thermodynamic equilibrium, the rate of local entropy creation inside the enclosure may be stated in dimensional form as:

$$S_{gen} = \frac{K_{nf}}{T_o^2}\left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right] + \frac{\mu_{nf}}{T_o}\left[2\left\{\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right\} + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right] + \frac{\sigma_{nf} B_o^2}{T_o^2} v^2 \quad (2.3910)$$

The dimensionless formulation of the local entropy generation rate may be stated as:

$$S_\theta = \frac{K_{nf}}{K_f}\left[\left(\frac{\partial \theta}{\partial x}\right)^2 + \left(\frac{\partial \theta}{\partial Y}\right)^2\right] \quad (2.40)$$

$$S_\psi = \xi \frac{\mu_{nf}}{\mu_f}\left[2\left\{\left(\frac{\partial U}{\partial X}\right)^2 + \left(\frac{\partial V}{\partial Y}\right)^2\right\} + \left(\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X}\right)^2\right] \quad (2.41)$$

$$S_{mf} = \xi \frac{\rho_{\mathrm{pf}}}{\rho_t} Ha^2 V^2 \quad (2.42)$$

$$S = S_\theta + S_\psi + S_{mf} \quad (2.43)$$

Where $S_\theta$, $S_\psi$, and $S_{mf}$ are used to represent dimensionless entropy generated by heat transfer, fluid friction, and magnetic field, respectively. And $\xi$ is used to represent the irreversibility distribution ratio, which may be described as:

$$\xi = \frac{\mu_f T_o}{K_f}\left(\frac{\alpha_f}{L\Delta T}\right)^2 \quad (2.44)$$

In Equations (46), and (47), the value of $\xi$ is constant and equal to 100. The production of global entropy may be computed as follows:

$$S_T = S_{\theta,\,\mathrm{Total}} + S_{\psi,\,\mathrm{Total}} + S_{mf,\,\mathrm{Total}} \quad (2.45)$$

The global entropy production due to heat transfer, fluid friction, and magnetic field are represented by $S_{\theta,\mathrm{Total}}$, $S_{\psi,\mathrm{Total},}$ and $S_{\mathrm{mf,\ Total},}$ respectively. These quantities are derived by the integration of the local entropy generating components throughout the whole domain:

$$S_{\theta,Total} = \int_\Omega S_\theta \, d\Omega \quad (2.46)$$

$$S_{\psi,Total} = \int_\Omega S_\psi \, d\Omega \quad (2.47)$$

$$S_{mf,Total} = \int_{\Omega} S_{mf} \, d\Omega \tag{2.48}$$

## 3.5. Bejan number

The Bejan number is used to quantify the entropy generation:

$$Be = \frac{S_{\theta}}{S_{\theta} + S_{v} + S_{mf}} \tag{2.49}$$

$Be_{avg}$ is the average Bejan number and is computed as:

$$Be_{\text{avg}} = \frac{S_{\theta,\text{ Total}}}{S_{\theta,\text{ Total}} + S_{\psi,\text{ Total}} + S_{mf,\text{ Total}}} \tag{2.50}$$

# Chapter III: Simulation of hybrid nanofluid in layered enclosure

# Simulation of a hybrid nanofluid in layered enclosure

## 1. Introduction

For nanofluids to be used as a possible heat transfer medium in the future, it is crucial to understand flow dynamics and heat transmission in nanofluids.In this chapter, numerical investigations are carried out using single phase approach to analyze the heat transfer and steady magneto-hydrodynamic natural convection in an enclosure with cold corrugated walls incorporating a hot and centered elliptical cylinder and partitioned into two layers. In the first layer, the nanofluid is freely flowing and in the second one, it saturates a porous medium. The main objective of this research is to analyze the effects of different nanoparticles concentrations and dimensionless parameters. The computational domain adapted for this work are presented herein. The geometry of the computational domain, mesh configuration, and validation are also described. Finally the numerical results are expressed in terms of distributions of isotherms, Nusselt number, and streamlines, and then discussed.

## 2. Geometry of the computational domain

The considred geometry for this work is a square with cold wavy sidewalls ($T_c$) and elliptical heated hole ($T_h$) at the center as shown in Figure 14. the enclosure is also divided into layers: a free nanofluid layer where the hybrid nanofluid can flow freely and a porous layer filled with porous media and hybrid nanofluid. The enclosure under investigation is loaded with ($Fe_3O_4$-MWCNT (50-50%) /$H_2O$) hybrid nanofluid and subjected to a uniform magnetic field with $B_0$ magnitude. The outside boundaries of the enclosure are seen as impenetrable.

### Boundary conditions

The boundary conditions explored in this computational domain are as follows:

For the top and bottom horizontal walls: $\frac{\partial \theta}{\partial Y} = 0, U = V = 0$

Right and left wall: $\theta = 0, U = 0, V = 0$

Around the elliptic surface: $\theta = 1, U = 0, V = 0$

On the interface wall between the nanofluid and the porous media layers:

$$U_{nf} = U_{po}, V_{nf} = V_{po}$$
$$(\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X})_{nf} = (\frac{\partial U}{\partial Y} + \frac{\partial V}{\partial X})_{po}$$
$$\left(\frac{\partial \theta}{\partial Y}\right)\text{nano layer} = \left(\frac{k_{eff}}{k_f}\frac{\partial \theta_{po}}{\partial Y}\right)\text{ porous layer}$$
$$\theta_{nf} = \theta_{po}$$

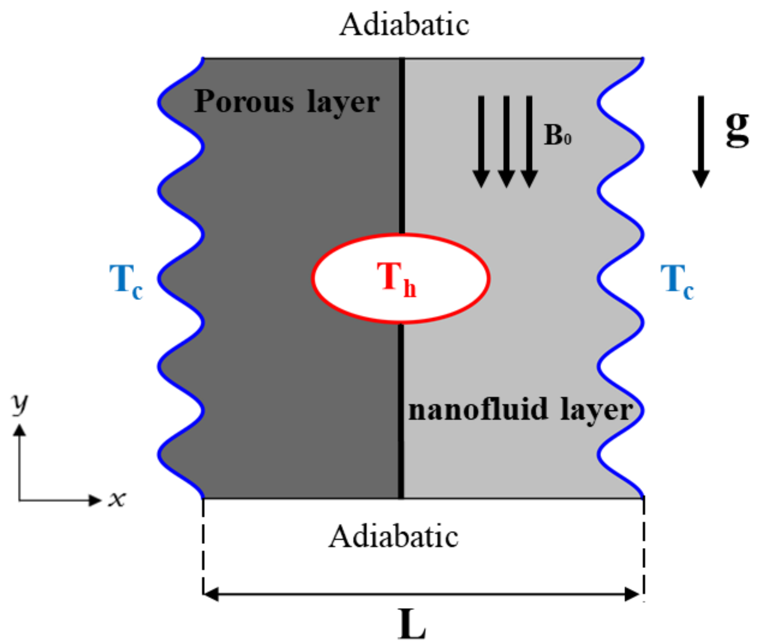



*Figure 14 Illustration of the computational domain and boundry conitions*

# 3. Mesh Configuration and Validation

## 3.1. Mesh Configuration

The the quality of the discretization utilized has an impact on the accuracy of numerical solutions. Since each mesh element serves as the foundation for a solution in finite element analysis, the distance between nodes directly impacts the correctness of the result. The mesh area of the mesh elements will be smaller and the distance over which the governing equation must be estimated will be reduced as the nodes go closer together. Therefore, the solution becomes more precise the more the mesh is refined. However, the number of equations that must be solved and the amount of computational power needed to arrive at a solution increase with the number of mesh elements present. An example of the mesh we used in this work is shown in Figure 15. From Figure 15, one can observe that there is a very fine mesh near cold and hot walls region, especially near complex geometry, and relatively less refined mesh elsewhere.

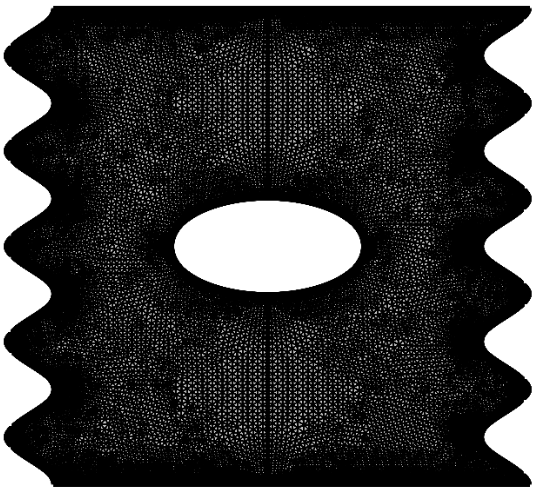


*Figure 15 Mesh sample*

We performed a grid convergence analysis for two configurations to determine the CFD solution's reliability and to keep the computational expenses down. The analysis of nanofluids MHD natural convection flow is done at Ra=$10^5$, Ha=0 Da=$10^{-2,}$ and φ=4% utilizing 6 distinct meshes, each with a different degree of refinement and element number. The outcomes are analyzed in terms of the average Nu number to ascertain how the mesh quality impacts the outcomes of CFD simulations. It has been found that there is no significant change in Nusselt number beyond the element number 531828 which is shown in Figure 16. Therefore, for the present study, the grid with 531828 element has been used to perform all the simulations.The results showed good convergence with this mesh.

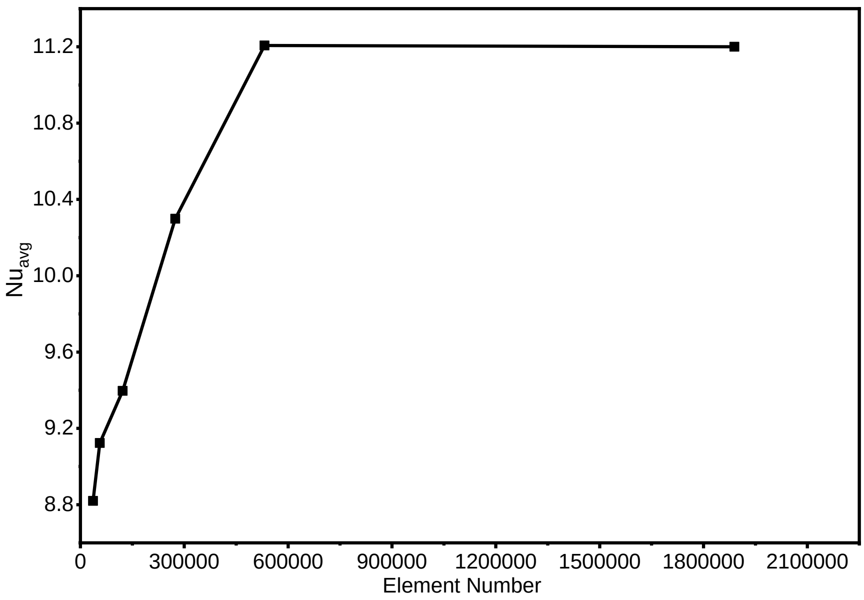



*Figure 16 : Comparison of Averge Nusselt number for different mesh element number.*

## 3.2. Validation

To ensure the precision of the used numerical technique, the thermal behavior is compared with the results reported by Khanafer *et al.* [120]. In their work, Khanafer *et al.* [120] numerically simulated the buoyancy-driven flow of nanofluids inside a 2D cavity. Figure 17 shows a comparison between their results and our results for the flow patterns and thermal fields across the cavity with very good agreement.

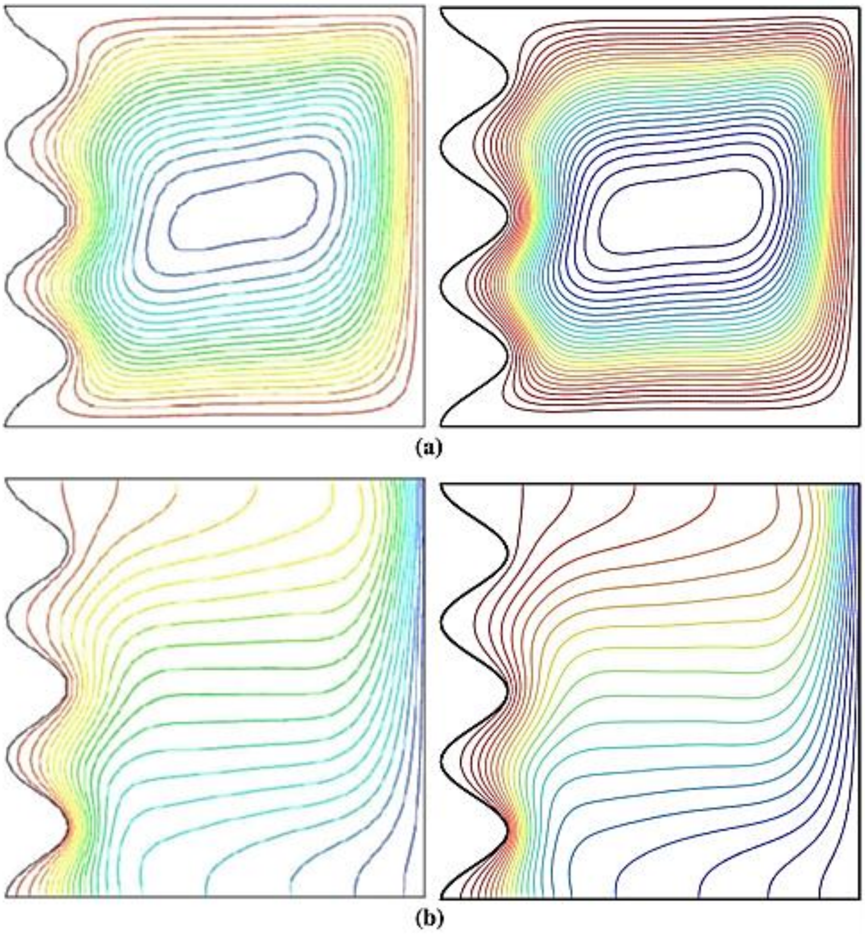


*Figure 17 Comparison between our result (right) and Khanafer et al. [120] (left) at Ra =$10^5$ (a) streamlines, (b) Isotherms.*

In addition, we also validated our results with the results of Ghasemi et al [121] where we found that the error is less than 2%, as seen in Figure 18.

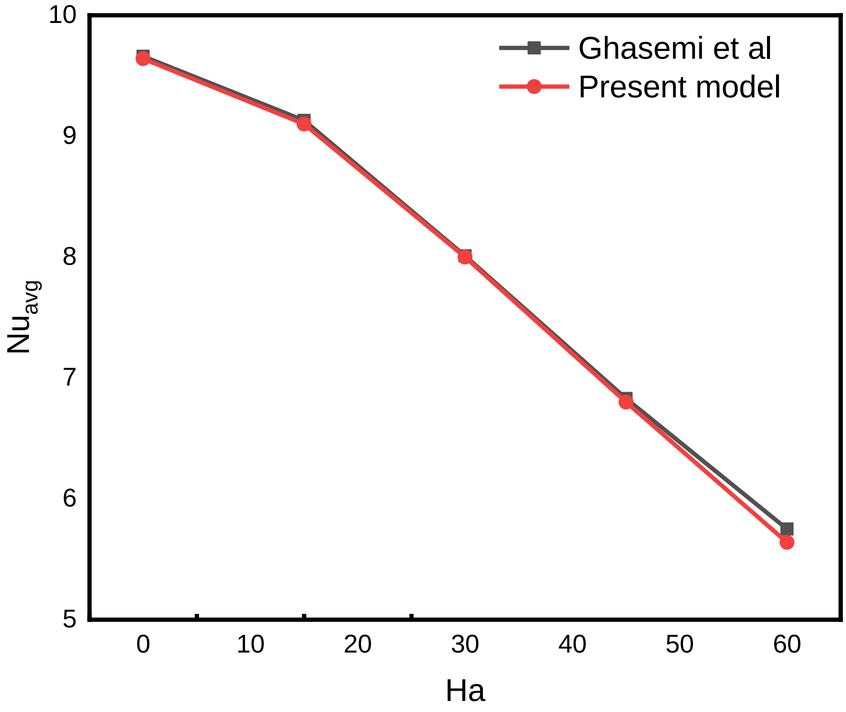



*Figure 18 Comparisons of present model with previous works*

# 4. Results and discussions

In this investigation, a numerical approach has been undertaken to review the impact of different controlling parameters. The first is the geometrical parameter the undulation number (N = 1, 3, 5, and 9) the others are fluid and heat parameters, for instance, Ra ($10^6 \geq Ra \geq 10^3$), Da ($10^{-2} \geq Da \geq 10^{-5}$) and Ha ($100 \geq Ha \geq 0$).

## 4.1. Effect of undulation number N

Figure 19 illustrates the impacts of the number of undulations on the isotherms and streamlines at Ra= $10^5$ and Ha=0. It could be observed that when N=1 there are two symmetric vortices in the hybrid nanofluid layer and one vortex in the porous layer and no matter the value of N the maximum absolute value of stream faction in the nanofluid layer is much greater than in the porous layer. We can elucidate this by the fact that the porous layer presents a higher restriction to the nanofluid flow. For N=3, there is not much change in the isotherms and the streamlines tend to align with the wavy shape of sidewalls of the cavity and the maximum absolute value of stream faction raises from $|\psi_{max}|^{N=1} = 6.6644$ to $|\psi_{max}|^{N=3} = 6.7315$. However, when we increased the value of N to 5 and 9, the narrow space between the waves grew smaller and consequently obstructed the circulation of the nanofluid leading to a decrease in $|\psi_{max}|$ value.

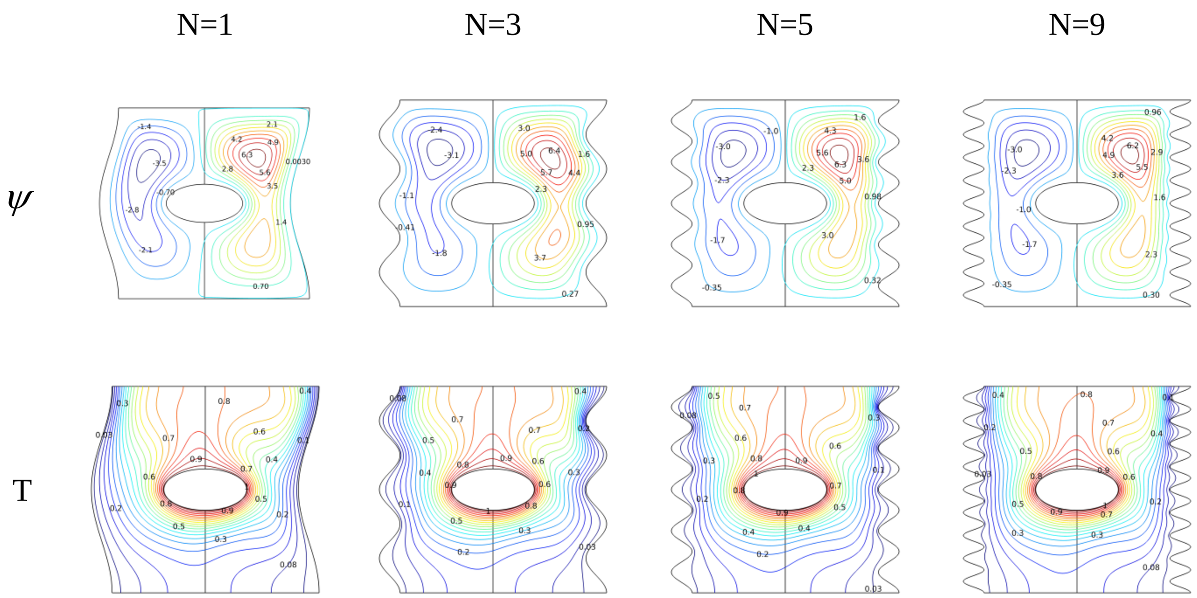



*Figure 19 Streamlines and isotherms evaluated by undulations number for Ra=$10^5$, Da=$10^{-2}$, and Ha=0*

## 4.2. Effect of Rayleigh number

Figure 20 depicts the isotherms and streamlines for various values of Ra number at $\phi$= 4%, and N = 5. On the grounds that the intensity of the convective flow has a straightforward correlation with the highest level of the $\psi$, and also because the rising level of Ra causes an increase in the $|\psi_{max}|$. Accordingly, as long as Ra rises, the intensity of the convective flow in the cavity rises. Moreover, whenever the Ra values escalate the streamlines in the middle region are extended in the x-direction, and the isotherms are deformed. This may be explained by the fact that at lower Ha and higher Ra numbers, convection is the heat transfer predominant mode.

Ra $10^3$ $10^4$ $10^5$ $10^6$

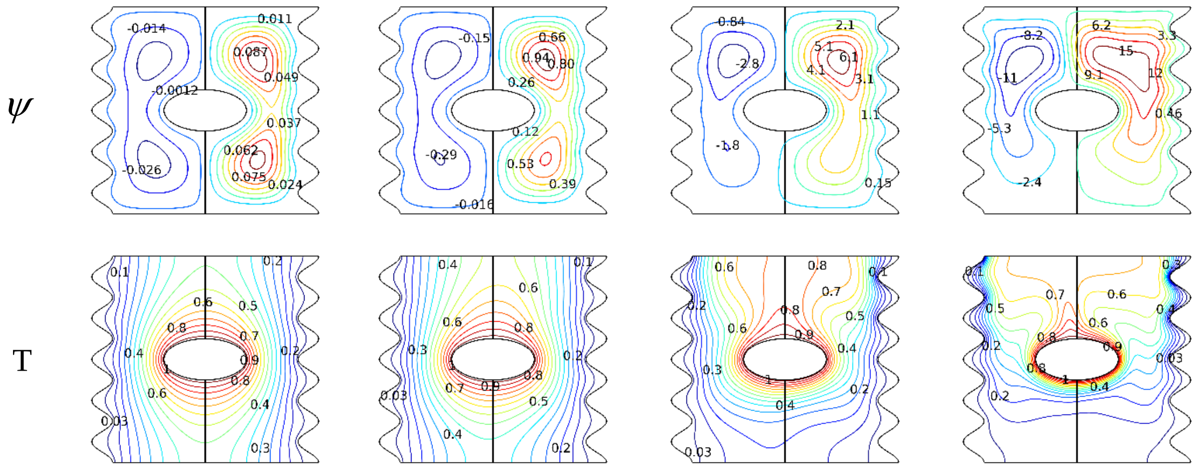



*Figure 20 Streamlines and isotherms evaluated by Ra number for Da=$10^{-2}$, N=5, and Ha=0*

## 4.3. Effect of Hartmann number

Figure 21 depicts the isotherms and streamlines for various values of Ha number at $\phi$= 4%, and N = 5. The data obtained indicate that the $|\psi_{max}|$ recedes and inevitably the strength of natural convection diminishes as Ha rises. Consequently, the conduction becomes the leading mode of heat transfer with the rising of the Hartmann number which is demonstrated by the uniform distribution of the isotherm contours at low Ra and high Ha numbers.

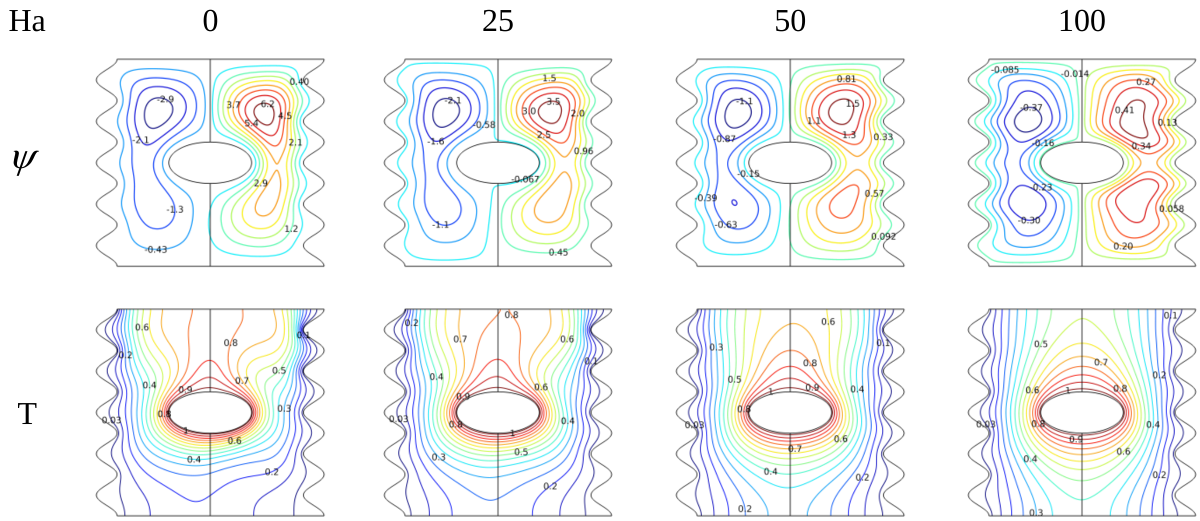



*Figure 21 Streamlines and isotherms evaluated by Ha number for Ra=$10^{5}$, N=5, and Da=$10^{-2}$*

## 4.4. Effect of Darcy number

Figure 22 presents the isotherms (θ) and streamlines (Ψ) of hybrid nanofluid (right region) and permeable medium saturated with similar hybrid nanoliquid (left region) for various Da at [Ra=$10^6$, φ = 0.04, Ha=0]. The strength of fluid flow structure is a growing function of Darcy number. In fact, this can be ascribed to the growing permeability in the saturated porous media which will cause additional nanofluid penetration, therefore improving the fluid flow and boosting $|\psi_{max}|$. Regarding the isotherms, they are allocated vertically at a low Da [Da=$10^{-5}$] for the reason that conduction phenomena dominate. When the Da escalates into [Da=$10^{-2}$] the isotherms contours alternating its configuration from vertical into horizontal, which is a sign that convection phenomena is dominant.

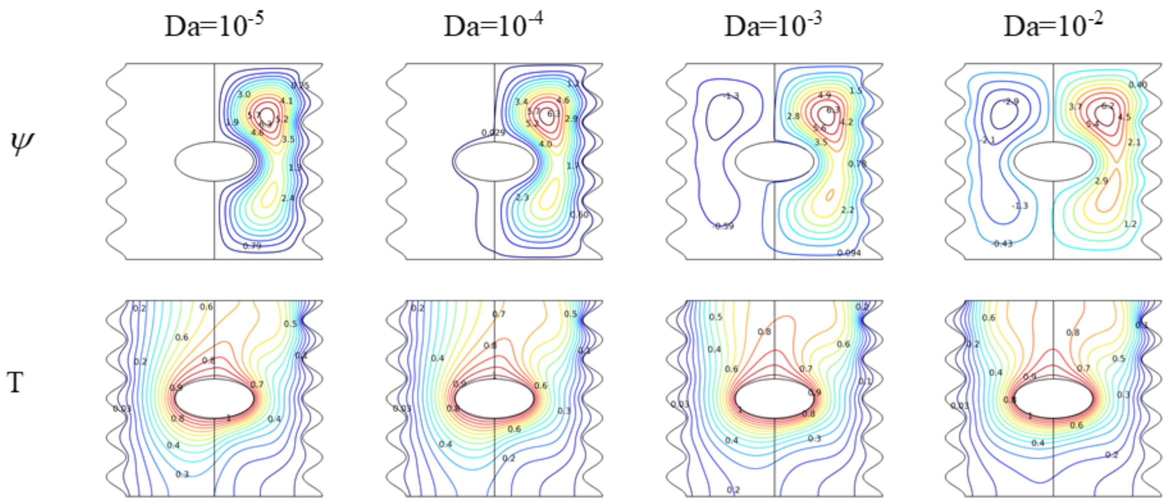
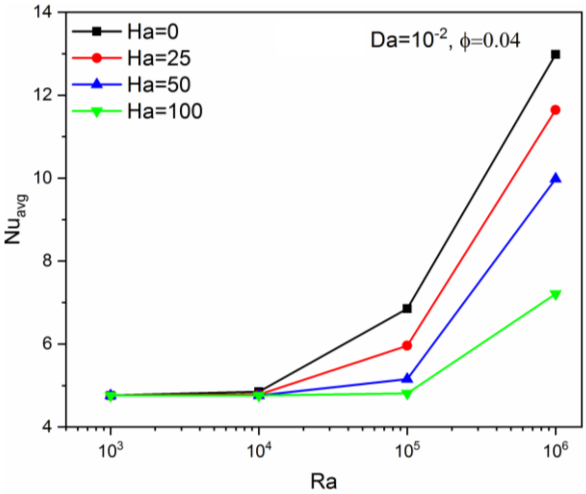


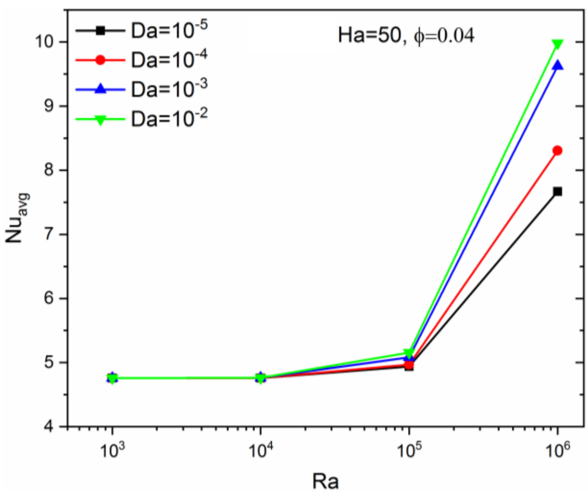

*Figure 22 Streamlines and isotherms evaluated by Da number for Ra $10^5$, N=5, and Ha=0.*

### 4.5. Effect of Da, Ha, φ, and N on $Nu_{avg}$

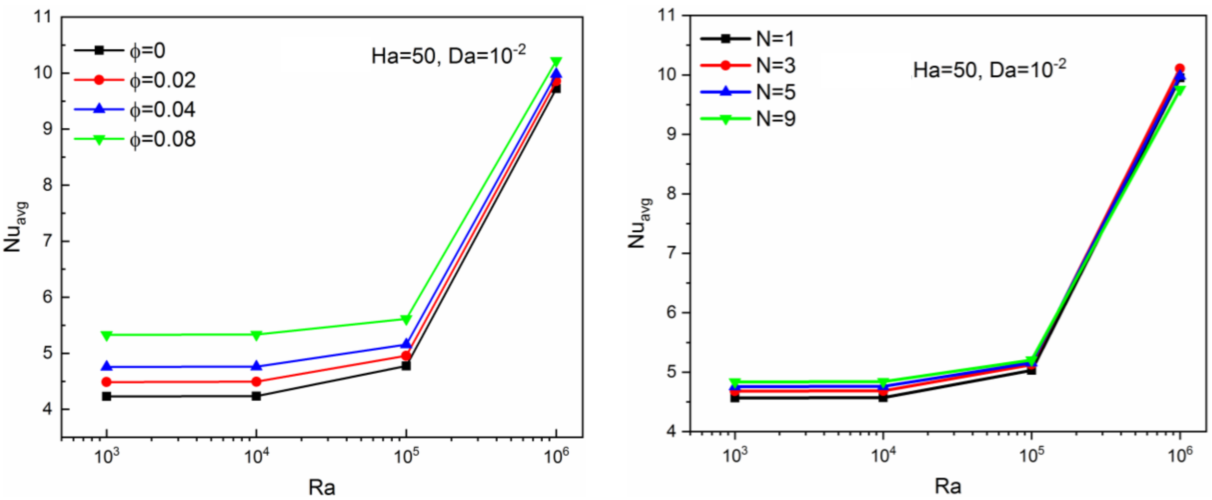
For a visual representation of the impact of Ha, N, Da, and Ra on the variation of $Nu_{avg}$ along the internal elliptical hot hole, the reader is referred to Figure 23. Figure 23(a) indicates that as the Rayleigh number goes up, the $Nu_{avg}$ ascends which implies that the role of the convection is superior to conduction however these results are completely reversed when the Hartmann number increases which means that the conduction is more dominant and it is significant to note also that this result is additionally prominent for elevated values of Rayleigh this observation can be attributed to the fact that the magnetic forces are acting in opposite directions with the gravity. Figure 23(b) demonstrates the consequence of the Da and Ra numbers on the $Nu_{avg}$ and implies that the augmentation of these parameters will enhance the $Nu_{avg}$ on account of growing the Da will reduce the degree of solid matrix resistance in the direction of fluid flow in the left zone of the enclosure which generates a surge in the convection we can also observe that at low Ra numbers the impact of changing Da is insignificant however it becomes more substantial as Rayleigh number increase. Figure 23(c) elucidates the influence of the φ and Ra on the $Nu_{avg}$ as can be understood rising the φ and the Ra will boost the $Nu_{avg}$ this is because the addition of nanoparticles to the fluid will elevate the viscosity of the nanofluid as well as its thermal. In addition, the impact of the undulation on the $Nu_{avg}$ is presented in Figure 23(d), where we can see that at low Ra (Ra= $10^3$) the Nu avg is directly correlated with the undulation number however this relationship, does not hold at higher Ra (Ra=$10^6$ ) where N=3 is the best option.




(a)




(b)




*(c)* *(d)*

*Figure 23 Effect of (a) Ha, (b) Da, (c) φ, and (d) N on Nu avg for different values of Ra.*

## 5. Conclusion

The impact of applying an external magnetic field on heat convection flow of hybrid $Fe_3O_4$-MWCNT/water nanoliquid within a cavity with cold corrugated walls incorporating a hot centered elliptical cylinder and partitioned into two layers is investigated. Along with the impact of various associated parameters such as the Ra, Ha, Da, and nanoparticles concentration on the isotherms, the streamlines, and the average Nu. The main findings from the investigation are as follows:

1. 1. When conduction is the primary mode of heat transfer at low Ra numbers (Ra 103), raising the wave number improves the heat transfer because the cold surface area increases. However, at high Ra numbers (Ra106), increasing the wave number has a detrimental impact on heat transmission because the wavy walls pose a flow obstruction.
2. As Ra, Da, and ϕ rise, the convective flow in the cavity is enhanced; as the Hartmann number increases, it is diminished.
3. In general, a better heat transfer may be accomplished at a higher nanoparticles concentration at low Ra numbers. On the other hand, the positive influence of raising the volume fraction of the nanoparticles will be somewhat diminished at high Ra values.
4. When $Ra \leq 10^3$, the magnetic field effect is unnoticeable. However, at high levels of the Ra number, the magnetic field exerts great restriction on the convective flow and heat

transfer. The increase in the Hartmann number from 0 to 100 reduces the average Nusselt number by 43.8% when $Ra=10^6$.

# Chapter IV: Simulation of hybrid nanofluid in a porous annulus space

# Simulation of a hybrid nanofluid in a porous annulus space

## 1. Introduction

The hydrothermal significance of natural convection flow through the horizontal annulus reveal most important implication and those geometrical shapes are introduced in enormous industrial and engineering implementations related to superheaters, heat exchangers, hydrogen fuel cells, gas turbines, solar collectors, vehicle engines, and turbomachinery etc. With this motivation, the current invistegation enlightens the natural convection heat transfer impacts of ($Fe_3O_4$-MWCNT) nanofluid flow through horizontal annulus filled with porous medium and subjected to magnetic field. The novelty of this work is presented by the special shape and different studied positions of the hot inner tube. The computational domain adapted for this work are presented herein. The geometry of the computational domain, mesh configuration, and validation are also described. Finally the numerical results are expressed in terms of distributions of isotherms, Nusselt number, and streamlines, and then discussed.

## 2. Geometry of the computational domain

The computational domain in this investigation is a porous annulus space between the outer circular cylinder maintained at a low temperature ($T_c$) and an inner Koch snowflake-shaped cylinder maintained at a high temperature ($T_h$) as depicted in Figure 24. Both the outside and interior boundaries of the enclosure are seen as impenetrable. The enclosures under investigation are loaded with porous media saturated with ($Fe_3O_4$- MWCNT (50-50%) /$H_2O$) hybrid nanofluid and subjected to a uniform magnetic field with $B_0$ magnitude.

**Boundary conditions**

- The boundary conditions explored in this computational domain are as follows:

Circular wall: $\theta = 0, \mathrm{U} = 0, \mathrm{V} = 0$

Around the Koch snowflake perimeter: $\theta = 1, U = 0, V = 0$

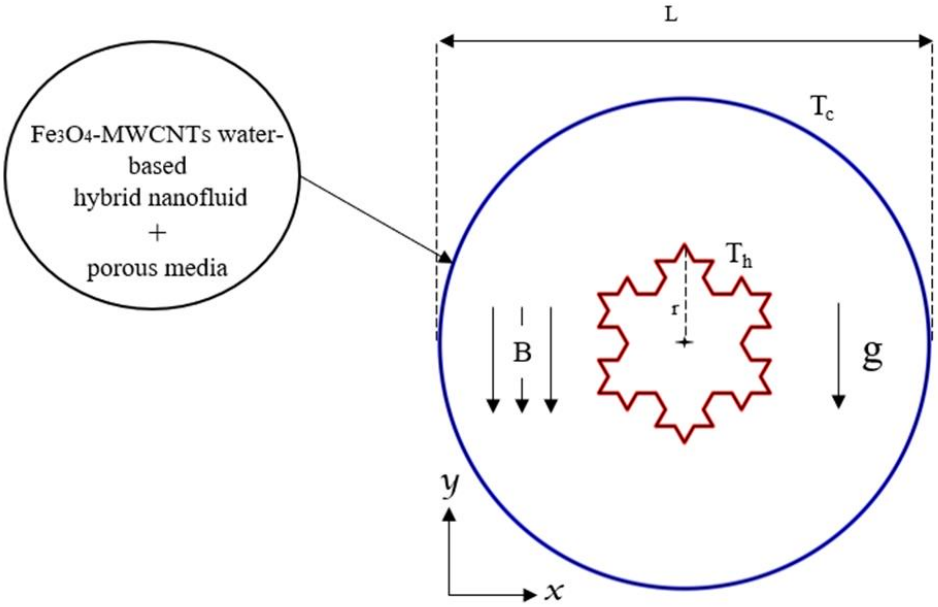



*Figure 24 Illustration of the computational domain and boundary conditions*

## 3. Mesh Configuration and validation

### 3.1. Mesh Configuration

An example of the mesh we used in this work is shown in Figure 25. From Figure 25, one can observe that there is a very fine mesh near cold and hot walls region, especially near complex geometry, and relatively less refined mesh elsewhere.

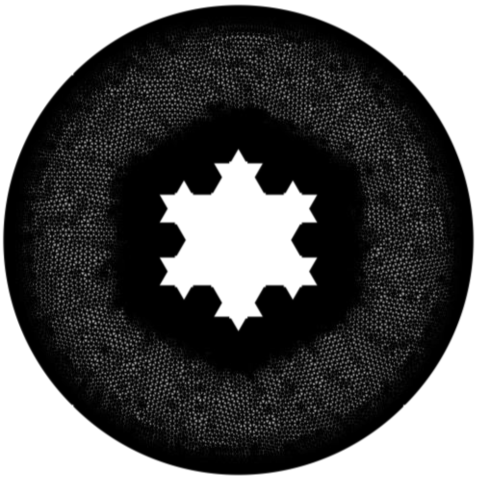


*Figure 25 Mesh sample*

We performed a grid convergence analysis to determine the CFD solution's reliability and to keep the computational expenses down. The analysis of nanofluids MHD natural convection flow is done at Ra=$10^5$, Ha=0 Da=$10^{-2,}$ and φ=4% utilizing 5 distinct meshes, each with a different degree of refinement and element number. The outcomes are analyzed in terms of the average Nu number to ascertain how the mesh quality impacts the outcomes of CFD simulations. It has been found that there is no significant change in Nusselt number beyond the element number 40060 which is shown in Figure 16. Therefore, for the present study, the grid with 40060 element has been used to perform all the simulations.The results showed good convergence with this mesh.

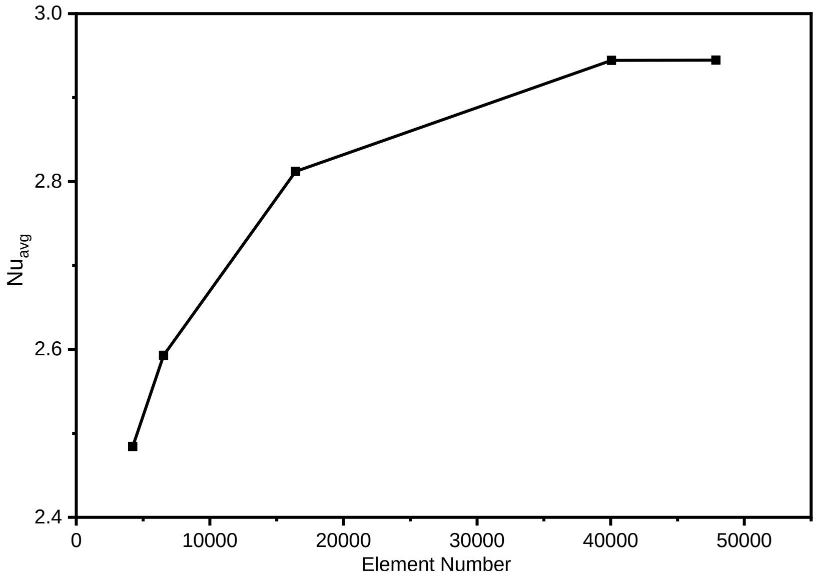



*Figure 26: Comparison of Averge Nusselt number for different mesh element number*

### 3.2. Validation

The flow behavior (represented by streamlines) and the thermal behavior (represented by isotherms) are compared to prior numerical findings of Sheikholeslami et al. [122] and given in Figure 27 to guarantee the numerical technique utilized and the mathematical model is correct.

*Figure 27 Streamlines (top) and isotherm contours (bottom) of the current study [right] and Sheikholeslami et al.[6] [left].*

# 4. Results and discussions

In this investigation, the flow behavior and free convection heat transmission of $Fe_3O_4$-MWCNT/Water hybrid nanofluid in a porous annulus consisting of an outer cold cylinder and inner heated Koch snowflake-shaped cylinder are presented. The streamlines (ψ), isotherms (T), and isotropic lines (S) are presented for different values of the Rayleigh number (Ra), Hartman number (Ha), Darcy number (Da), nanoparticle volume percentage (ϕ), and the position of the hot Koch snowflake-shaped cylinder (five cases).

## 4.1. Effect of Rayleigh number

In Figure 28 the impact of increasing the Ra number on the contours of streamlines, isotherms, and isotropic lines for Da = $10^{-2}$, Ha = 0, and $\phi$ =4%, and Ra numbers $10^3$-$10^6$ is presented. The purpose of describing these contours is to investigate the changes in buoyancy force in the cavity on the performance of flow and heat transfer parameters. Increasing the Ra number is possible by changing the temperature between the hot and cold sources. By raising this parameter, the buoyant force of the fluid is intensified, which is the primary source of the fluid circulatory movement which increases the absolute value of the stream function. The increment of the flow intensity inside the cavity accelerates the flow, resulting in a more diverse temperature distribution between the hot and cold sources and the appearance of a plume in the isotherms. Zones with lower heat transmission will develop only in those sections of the cavity where the circulation is restricted due to the unique construction of the inner cylinder, where the temperature distribution is not uniform and has a greater value. Also, in these areas, due to the indirect movement of the fluid, the flow dissipation is particularly significant at higher Ra numbers. Therefore, the amount of irreversibility around the hot barrier is significant and it increases as the Ra number raises.

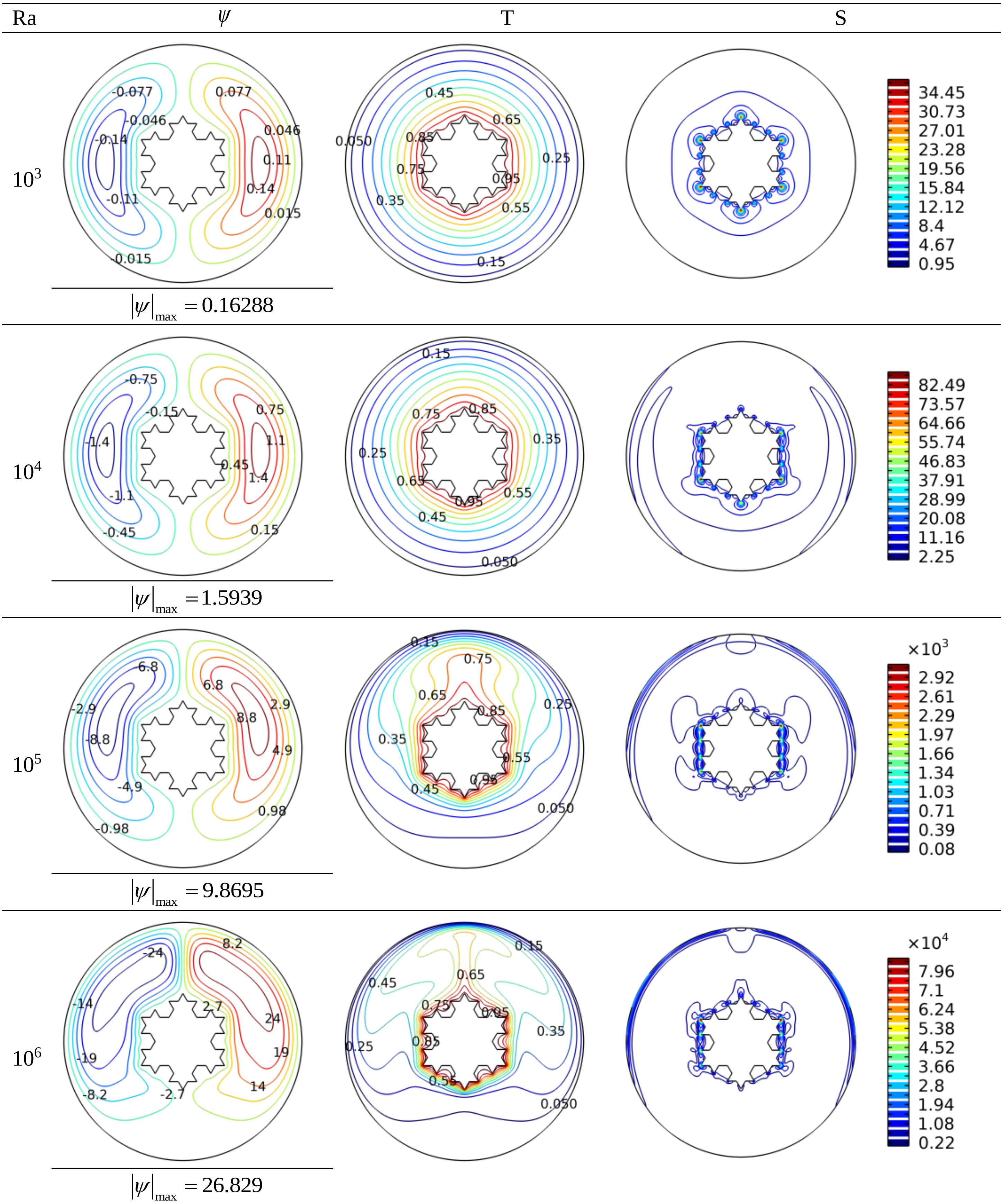



*Figure 28 Ra number influence on streamlines and isotherms for Da=$10^{-2}$, Ha=0, and $\phi$ =4%.*

## 4.2. Effect of Darcy number

In the contours of Figure 29, the streamlines, isotherms, and isotropic lines are represented as the Darcy number varies for Ra = $10^5$, Ha = 0, and $\phi$ =4%. In these profiles, the flow performance and heat transmission of the examined design is compared with the variations in the permeability of the enclosure. As the Da number increases, the penetration of the flow cross-section in the cavity increases, and the flow circulates in the cavity with less dissipation due to the buoyancy force. Therefore, at higher Da numbers, the flow intensity is amplified, and the mass flow rate is intensified at each section of the cavity. On the other hand, heat dissipation improves with increasing Da number, and temperature gradients decrease. The created irreversibility in the cavity is affected by the reduction of the Da number due to the intensification of the hot areas and the decrease of the fluid velocity in the lower Da numbers. Amplifying the Da number enhances heat transfer and fluid flow which in turn enhances irreversibility due to heat transfer thus boosting entropy in the cavity.

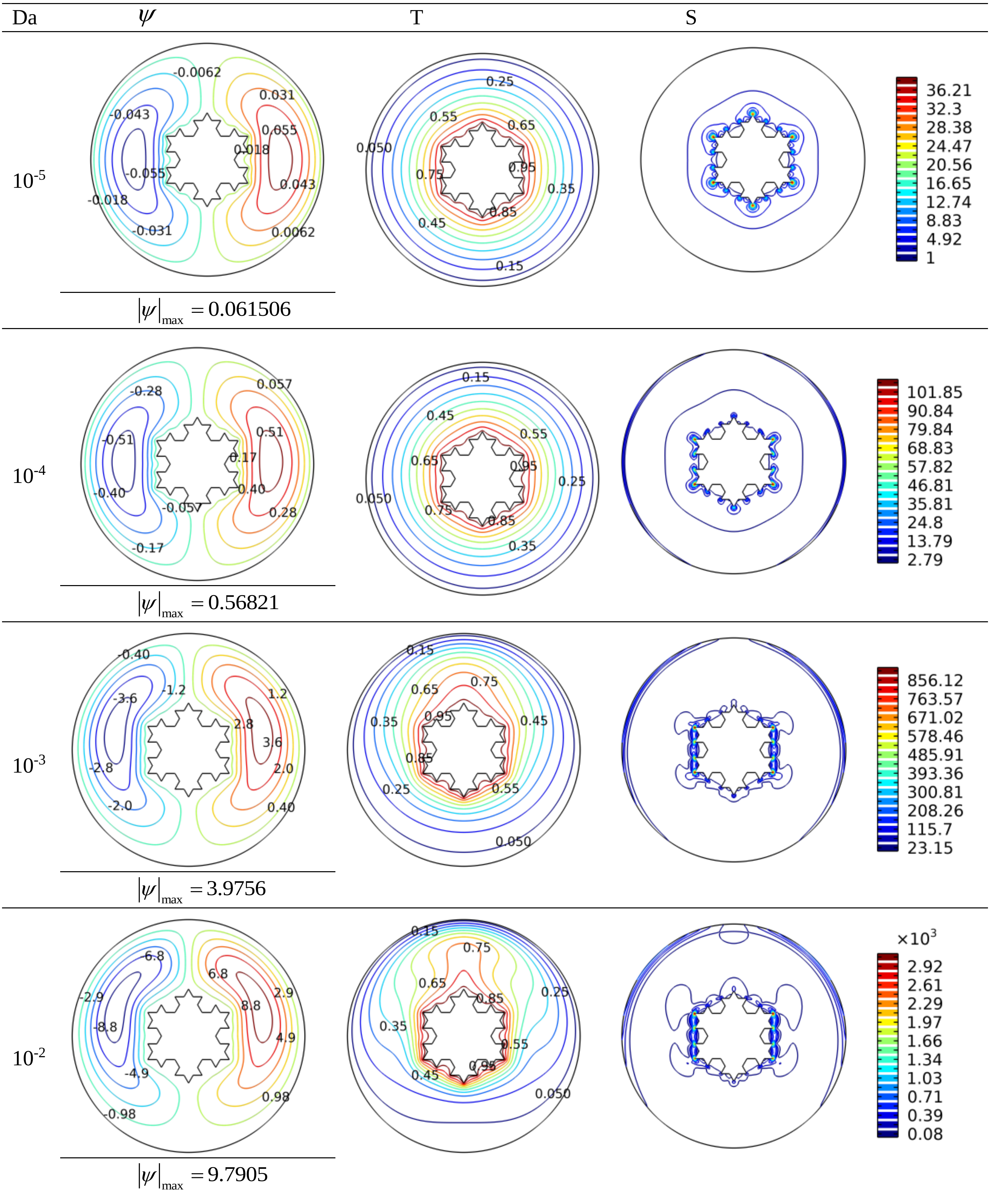



*Figure 29 Da number influence on streamlines and isotherms for Ra=105, Ha=0, and $\phi$ =4%.*

### 4.3. Effect of Hartmann number

The contours of Figure 30 show the effect of increasing the Ha number on the streamlines, isotherms, and isotropic lines for the values of Ra = $10^5$, Da = $10^{-2,}$ and $\phi$ =4%. In these contours, the studied geometry's flow performance and heat transfer are compared with changes in Lorentz force represented by the Hartmann number. Applying Lorentz force, if not in the direction of flow, causes the flow velocity to be depleted and fluid flow in the cavity to be impeded. Also, in the inner hot parts, if the application of the magnetic field is not in line with the gravitational force, it will cause the fluid to flow slowly from the hot surfaces, which will create parallels isotherms, indicating that conductive heat transfer becomes dominant in the cavity when the Hartmann number rises. The nanofluid flow between the surfaces of the hot Koch snowflake and the surrounding area will move slowly due to the Lorentz force and even slower between the angled surfaces, thus increasing the cavity temperature in these zones. Between the dimensional temperature distribution diagrams, parts such as the surfaces on the hot barrier and the surrounding area will move slowly due to the Lorentz force between the angled surfaces, and the flow rate depreciation is significant, hence the cavity temperature in these areas, especially the parts around the source will be increased. Due to the lack of uniform temperature distribution and velocity depreciation in the areas around the hot source, the amount of generated entropy has increased. Furthermore, as the Ha number raises the heat transfer and flow velocity degrade which reduces entropy production.

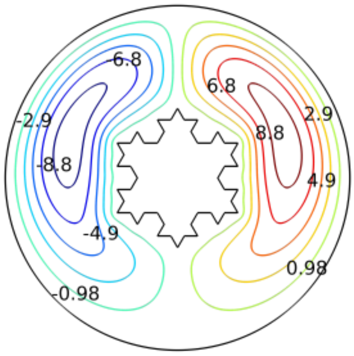
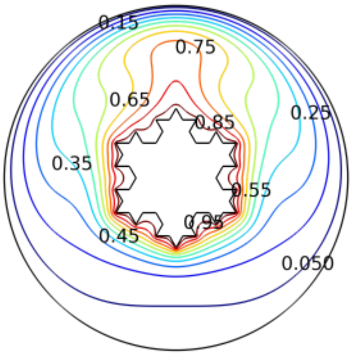
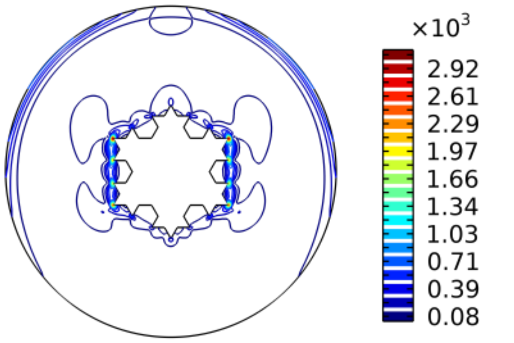
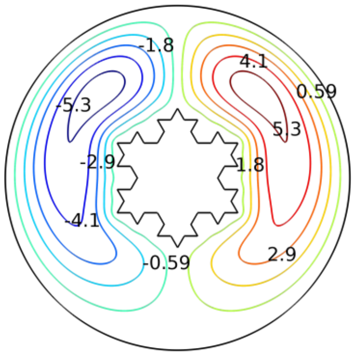
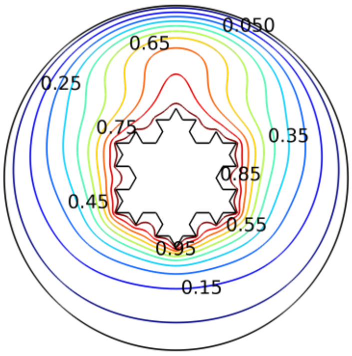
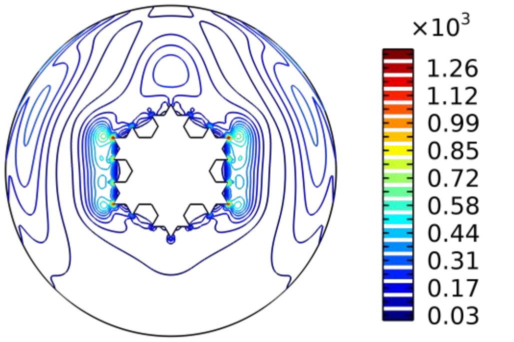
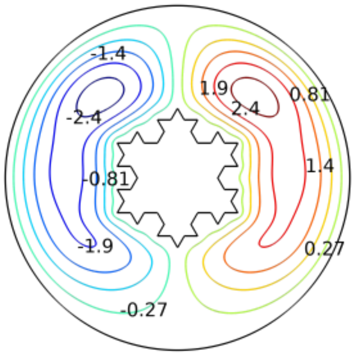
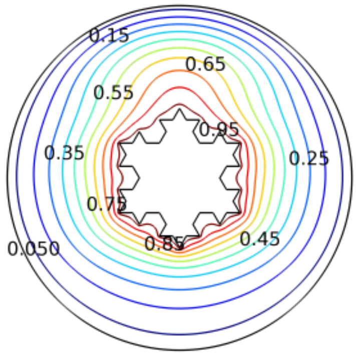
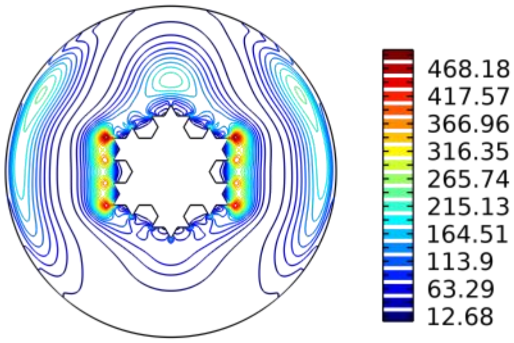
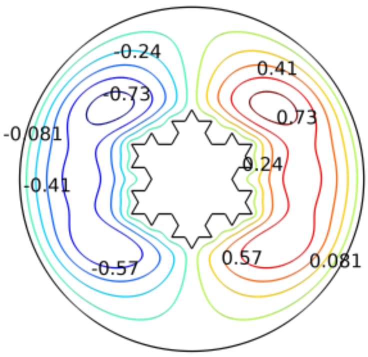
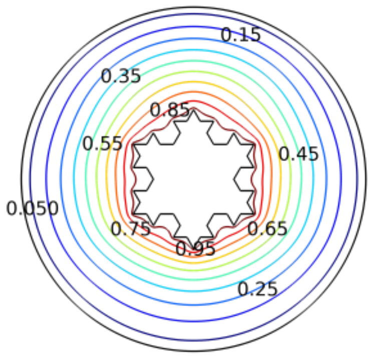
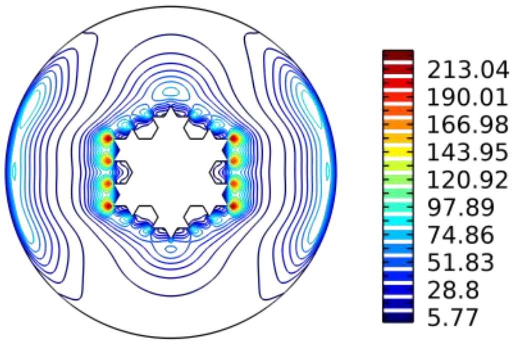
| Ha | $\psi$ | T | S |
|---|---|---|---|
| 0 | <br>$\lvert\psi\rvert_{max} = 9.7905$ |  |  |
| 25 | <br>$\lvert\psi\rvert_{max} = 5.8537$ |  |  |
| 50 | <br>$\lvert\psi\rvert_{max} = 2.7108$ |  |  |
| 100 | <br>$\lvert\psi\rvert_{max} = 0.81302$ |  |  |

*Figure 30 Ha number influence on streamlines and isotherms for Ra=$10^5$, Da=$10^{-2}$, and $\phi$ =4%.*

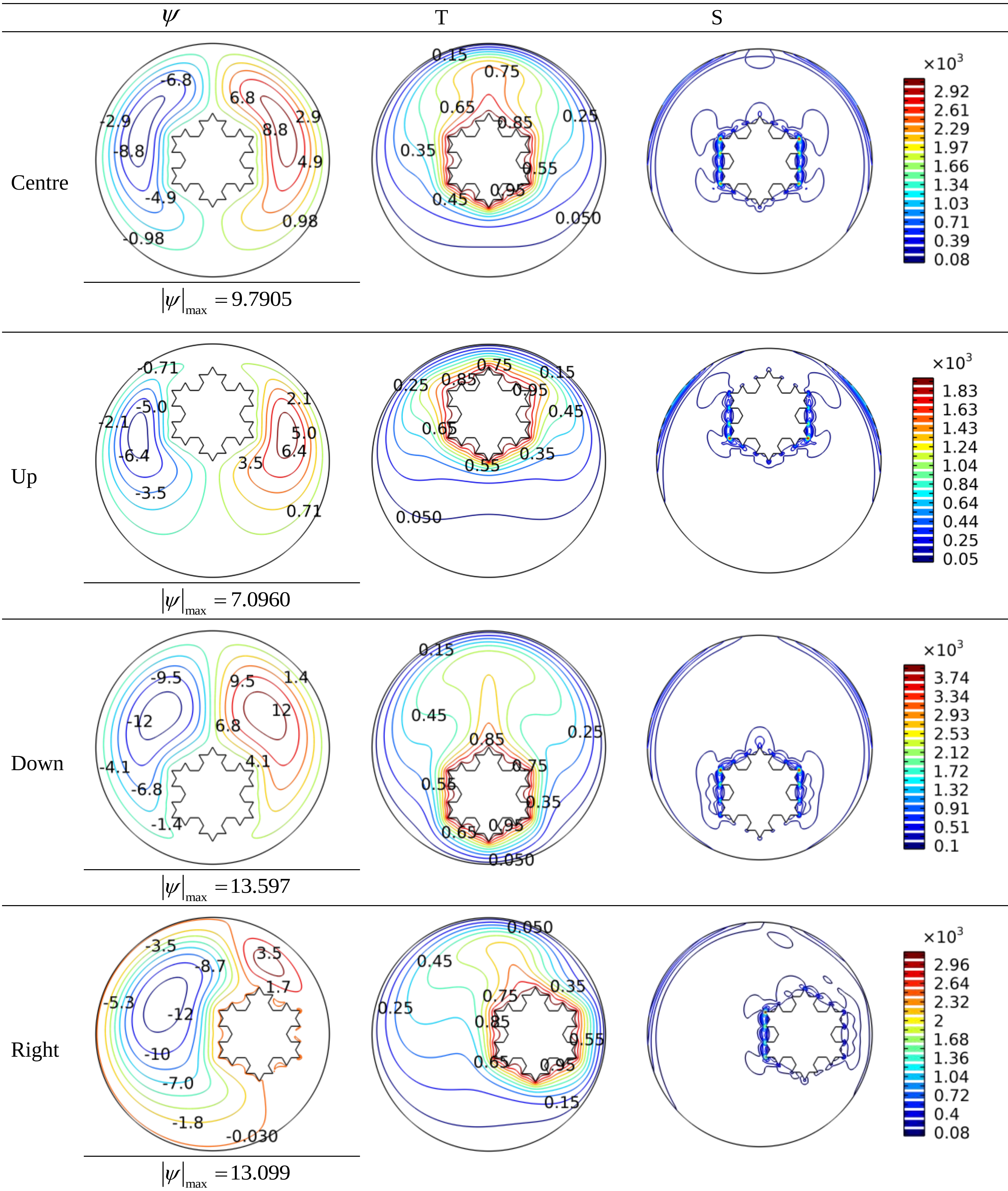
## 4.4. Effect of the hot Koch-snowflake position

In the contours of Figure 31, the impact of the hot Koch-snowflake-cylinder placement on the streamlines, isotherms, and isotropic lines for the values of Ra = 105, Ha=0, Da = 10-2, and ϕ =4% is presented. In these contours, the flow and heat transfer performance of the studied geometry is described and plotted with changes in the position of the hot inner cylinder. Placing the Koch snowflake in different parts of the cavity can disturb the mass balance and influence the convection field of natural convection.

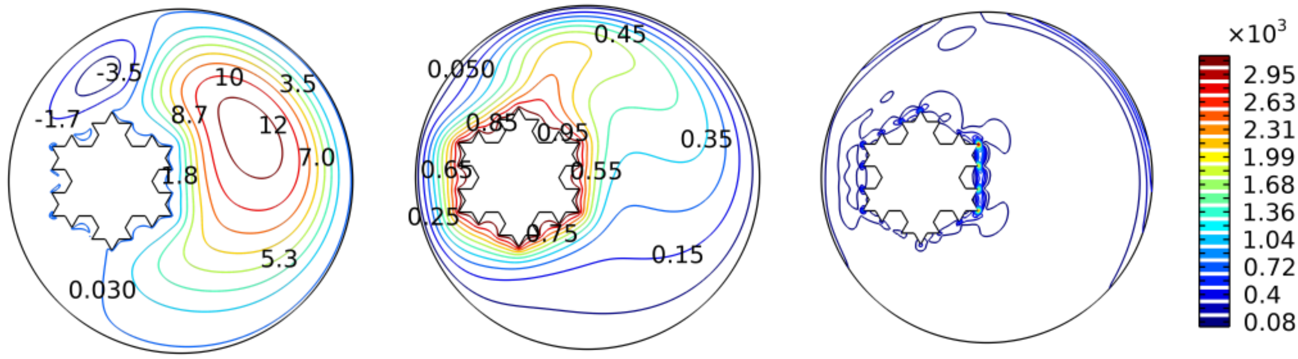
The hot Koch snowflake being placed in the bottom portion of the cavity maximizes the area available for the convection field above the hot cylinder. This lengthens the vortex's length and strengthens the fluid's momentum as it circulates within the hollow. The size of the plume in isotherms increases as a result of this improvement in natural convection. On the other hand, the placement of the hot Koch snowflake in the upper part of the cavity leads to less space for natural flow above the inner cylinder and causes the thermal plume to diminish.

Placing a barrier on the left or the right sides of the cavity also disturbs the temperature balance in parts of the cavity where the fluid velocity decreases. In addition, the flow circulation in the left and right cases exhibits a big rotating eddy adjacent to the inner cylinder and a smaller eddy above it rather than the two symmetrical eddies found in other situations.

The highest entropy production is recorded when the Koch cylinder is moved upward which may be explained by an increase in natural convection currents that increase irreversibility owing to friction and heat transfer.


ψ
T
S
Centre
$|\psi|_{max} = 9.7905$
×10^3
2.92
2.61
2.29
1.97
1.66
1.34
1.03
0.71
0.39
0.08
Up
$|\psi|_{max} = 7.0960$
×10^3
1.83
1.63
1.43
1.24
1.04
0.84
0.64
0.44
0.25
0.05
Down
$|\psi|_{max} = 13.597$
×10^3
3.74
3.34
2.93
2.53
2.12
1.72
1.32
0.91
0.51
0.1
Right
$|\psi|_{max} = 13.099$
×10^3
2.96
2.64
2.32
2
1.68
1.36
1.04
0.72
0.4
0.08

Left




$|\psi|_{max} = 13.099$

*Figure 31: Koch snowflake's position influence on streamlines and isotherms for Ra=105, Da=10-2, Ha=0, and $\phi$ =4%.*

## 4.5. Effect of Da, Ha, φ, and inner tube postion N on Nu $_{avg}$

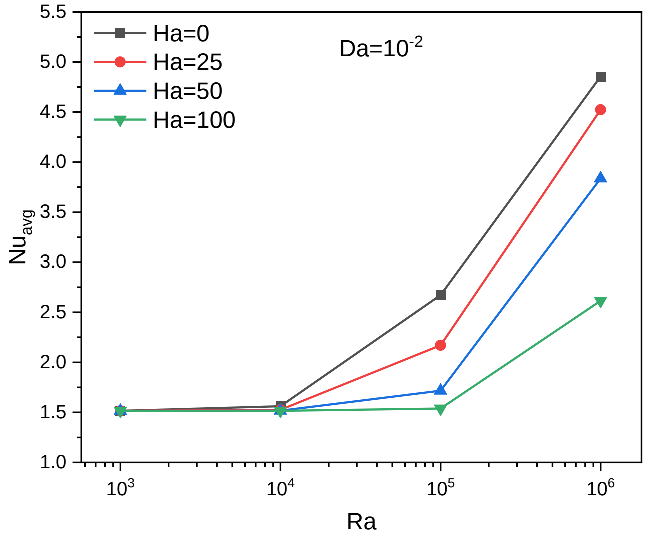
The changes in the average Nusselt number as a function of factors such as the inner tube postion , Ha number, Da number, and volumetric fraction of nanoparticles are depicted in Figure 32 as a function of Ra numbers from $10^3$ to $10^6$.

Figure 32 (a) presents the changes in the $Nu_{avg}$ affected by different Lorentz force values as a function of the Ra number. Significant changes in Nuavg are triggered by an increase in Ha, especially at higher values of Ra number. In fact, due to the direction of the magnetic force, the Lorentz forces are hindering the buoyancy forces. Thus, increasing the Ha number hinders the convective flow of the nanofluid, which reduce the average Nusselt number. Even though, increasing the Lorentz force strengthens the separation of the flow in the upper part of the cold source and the separation of the hot flow in the lower part of the inner cylinder. At Ra number less than $10^4$, the profiles of Figure 32(a) shows that the natural convection is weak and the heat transfer phenomena is similar to conduction, and increasing the Ha value has a weak impact on the rate of heat transfer.

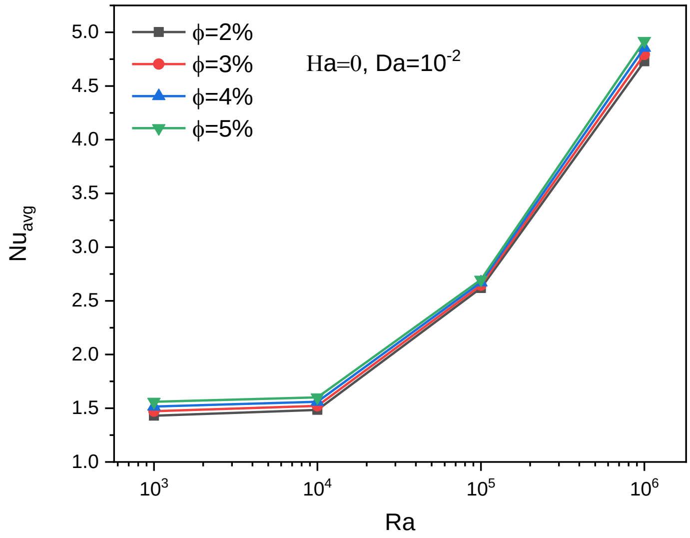
The changes in the $Nu_{avg}$ versus nanoparticles concentrations are plotted in Figure 32 (b). This investigation is performed without applying a magnetic field and Da = $10^{-2}$. The presence of solid nanoparticles in the base fluid will improve its thermal conductivity which facilitates heat transmission. Increases in the aforesaid attribute may enhance the Nusselt number in the examined geometry. On the flip side, by incorporating more solid nanoparticles into the base liquid, the viscosity may be increased. These rises in the viscosity of the nanofluid may reduce the intensity of the flow. Generally, raising the concentration of solid nanoparticles as shown in the plots of Figure 32 (b) has had a modest effect on the increase of the Nusselt number, and this remains true for practically all Ra values.

The impact of changing the Da number on the $Nu_{avg}$ behavior is plotted in the diagrams of Figure 32 (c). The porous media permeability inside the enclosure grows as the Da number increases. Reducing the permeability of the flow cross-section obstructs the fluid circulation path and depletes the fluid movement. The predominant mechanism of fluid motion in the annulus is with the help of thermosyphon force. This mechanism is formed as a result of the differences in the nanofluid density in the hot and cold zones of the annulus. The flow restriction caused by lowering the Da number will slow natural convection, which will therefore reduce the rate of heat transfer. The influence Ra number has on the Nuavg is essentially eliminated when the permeability is too low ($Da=10^{-5}$), indicating the dominance of conduction in this situation.

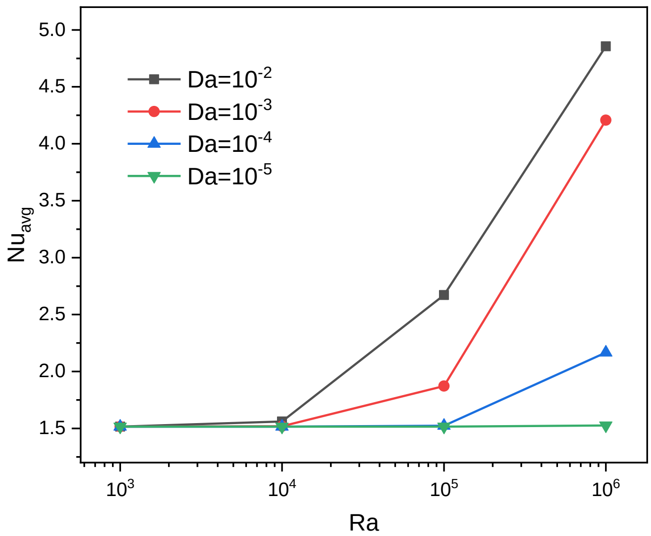
The variations in $Nu_{avg}$ behavior caused by displacing the hot inner cylinder in the cavity for 5 different cases are plotted in the diagrams of Figure 32 (d). The position of the hot inner cylinder can strengthen the fluid circulation or obstruct the fluid flow. For all Ra values, the effect of the hot inner cylinder location for both left and right cases is the same due to the same boundary conditions and only the change of direction of flow. The variation of the $Nu_{avg}$ versus the position of the hot inner cylinder in the cavity is limited at low Ra values ($Ra<10^4$). The $Nu_{avg}$ was lower in the center case than in any other case. For high Ra values, the worst-case situation (lowest value of $Nu_{avg}$) occurs when the heated inner cylinder is positioned at the top of the cavity because the area above the heated inner cylinder is limited and the larger space below it is where the hot source is above the cold source, making it difficult for natural convection to develop. The heated inner cylinder should be placed near the bottom of the cavity because doing so increases the distance between the lower hot source and the higher cold source, strengthening natural convection and intensifying liquid circulation from the lower hot source to the top cold source.



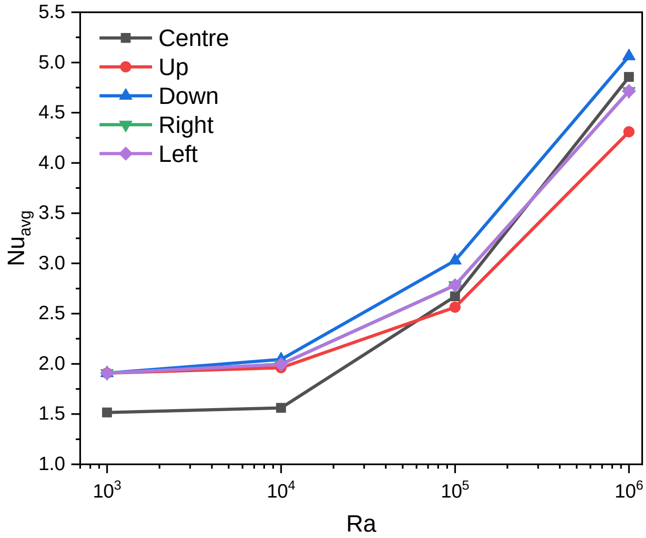

*(a)*




*(b)*




*(c)*




*(d)*

*Figure 32 Effect of (a) Ha, (b) φ, (c) Da, and (d) inner tube postion on Nu avg for different values of Ra.*

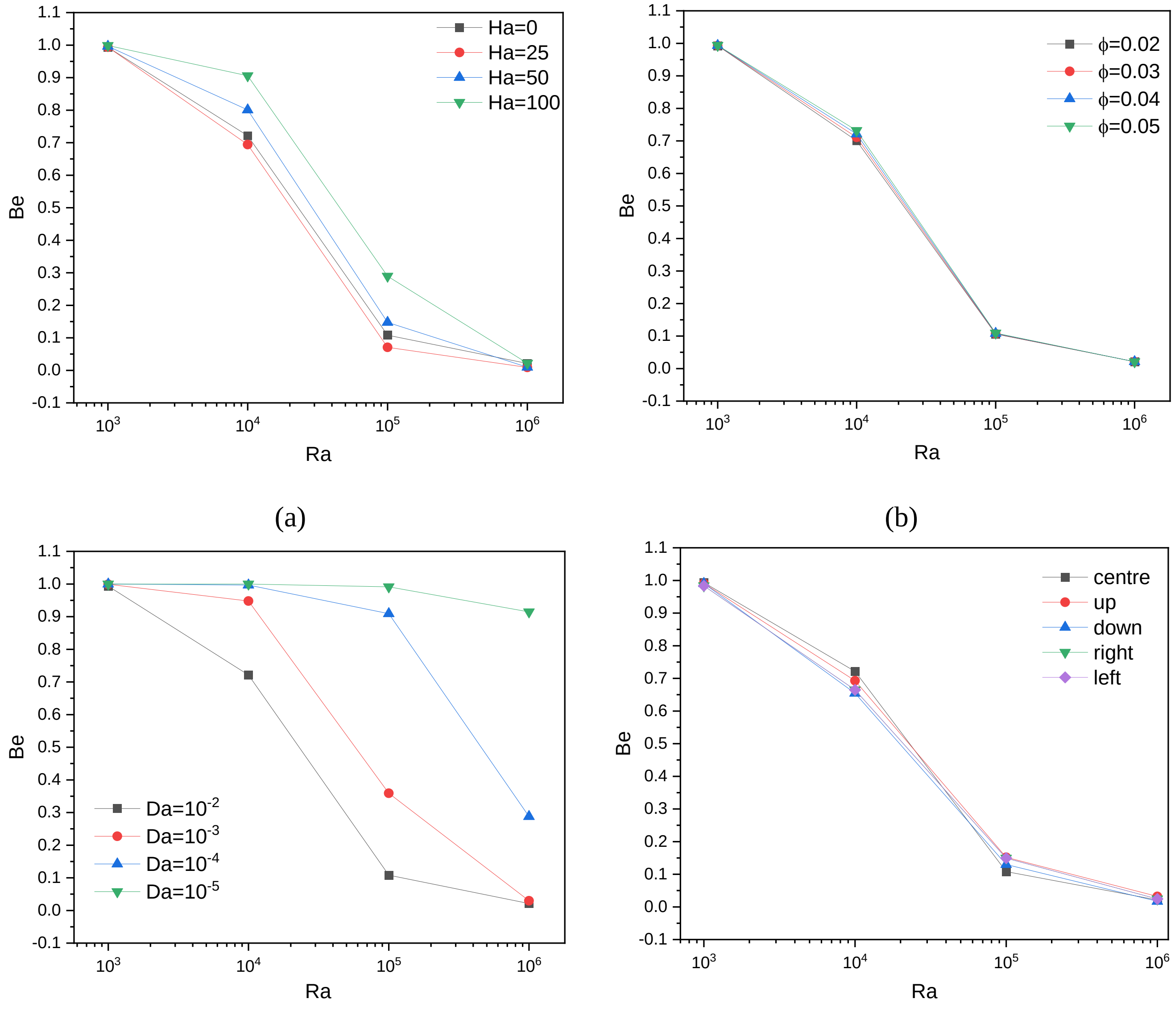
## 4.6. Effect of Da, Ha, φ, and inner tube postion on $Be_{avg}$

The variations of the Bejan number in the diagrams of Figure 33 are plotted at Ra =$10^3$ to $10^6$ with increasing Ha number, Da number, the volumetric fraction of nanoparticles, and hot cylinder location. The values of the Bejan number due to the application of different Ha numbers are plotted in Figure 33 (a). Accelerating heat transfer between hot and cold sources is accomplished by increasing the Ra number and amplifying the flow rate inside the chamber. By increasing the Ra value, the irreversibility associated with insufficient heat dissipation and the formation of hot zones is reduced, and the behavior of Bejan number diagrams trends toward zero. By increasing the Ra value and optimizing fluid motion and heat dispersion, the friction factor may be increased. The range of changes in these graphs demonstrates that for low Ra values, the Bejan number tends to be 1, suggesting a considerable rise in cavity temperature gradients and growth of the thermal boundary layer at low nanofluid velocities. By increasing the Ha number, the irreversibility is strengthened and the Bejan number values are strengthened. When Ra values are low, raising the Ha value increases fluid stagnation and therefore the temperature differential. At higher Ra values, the presence of high-intensity Lorentz forces impairs fluid flow and raises the friction factor. Due to the low velocity of the fluid at Ra number $10^3$, raising the Ra number has an influence on the Bejan number changes, and its value is determined only by the expansion of temperature gradients and is nearly constant. Due to the intensification of the fluid motion caused by the increase in buoyancy force, the Bejan number is not dependent on the Lorentz force or its intensity in Ra number $10^6$, and the Bejan number is a constant value.

In the diagrams of Figure 33 (b), the behavior of Bejan number values is displayed as a function of the volumetric percentage of nanoparticles added. Increases in the volumetric fraction of nanoparticles have a limited influence on changes in the Bejan number. The inclusion of nanoparticles may cancel out fluctuations in the Bejan number at various volume fractions, and the graphs show a nearly steady trend. Increased viscosity and density may be attained when adding more solid nanoparticles to promote heat transmission in the nanofluid. Furthermore, viscosity alters the friction factor behavior and increases the irreversibility of friction. Improved thermal conductivity, on the other hand, decreases temperature gradients and mitigates irreversibility caused by a non-uniform temperature distribution.

The curves in Figure 33 (c) illustrate the trends of Bejan number behavior as a function of changes in Da and Ra numbers. The presence of porous media in a cavity with varying degrees of permeability may have a considerable effect on the movement of the fluid, resulting in dramatic fluctuations in flow velocity degradation. The reduction in Da number in the flow cross-sectional area impedes fluid’s movement. Permeability diminishes as the Da number falls and the temperature gradient grows which explains why at a low Da value ($Da=10^{-4}$ and $Da =10^{-5}$) Be number didn’t reach 0 even when $Ra =10^{6}$.

The illustrations in Figure 33 (d) show the effects of moving the heated inner cylinder in the cavity for five different cases. Limited alterations in the Bejan number may occur when changing the location of the heated inner cylinder in the cavity.




(c) (d)

*Figure 33 Effect of (a) Ha, (b) φ, (c) Da, and (d) inner tube postion on Be $_{avg}$ for different values of Ra.*

# 5. Conclusion

This investigation examined the natural convective flow of $Fe_3O_4$-MWCNT/water hybrid nanofluid with various volumetric fractions from 0% to 5%. This study aimed to investigate the influence of the hot inner Koch snowflake-shaped cylinder location, and different values of the Ra, Ha, Da on natural convection of hybrid nanofluid inside a porous annulus cavity. The findings of the present study can be summarized in the following points:

1. A higher intensity flow will develop in the annular enclosure for high Ra, nanoparticle concentration, and Da and low Ha. The temperature distribution will be more inconsistent and convective heat transfer will be enhanced.
2. Due to the shape of the Koch snowflake-shaped cylinder, the flow is trapped between the angled sections, and the temperature distribution in these areas is not uniform and has a higher value.
3. The bottom of the enclosure is the best location for the Koch snowflake-shaped cylinder from the standpoint of heat transmission.
4. By increasing the Ra number and amplifying the flow rate in the cavity, the heat transfer between the hot and cold sources is accelerated.
5. As the Darcy number rises, the convective flow becomes stronger owing to an increment in the permeability of the medium.
6. As expected, the presence of solid nanoparticles improves thermal conductivity and hence improves heat transfer.
7. At the highest Ra, increasing Ha from 0 to 100 decreased Nuavg by 50 %.
8. Placing the hot Koch snowflake-shaped cylinder at the bottom of the annulus enclosure results in the highest Nuavg compared to other positions.
9. Be=1 signifies that entropy is generated solely by heat transfer irreversibility while Be=0 shows that total entropy is generated by fluid friction irreversibility only. When Ra rises the Bejan number tends which indicates that raising Ra enhances the convective flow which increases the irreversibility due to fluid friction
10. It was found that, at the highest, Ra, decreasing Da from $10^{-2}$ to $10^{-5}$ reduced Nuavg by 70 %.
11. The higher the flow surface permeability, the less obstruction to the fluid motion, and the fewer irreversible effects of its temperature gradients.

# General Conclusion and Future perspective

# General Conclusion

Numerical investigations of natural convection flow of hybrid nanofluid have been studied in two enclosures. the first is a square with cold wavy sidewalls and elliptical heated hole at the center as shown in Figure 14. this enclosure is also divided into two layers: nanofluid layer and porous layer f. The second is porous annulus space between a cold outer circular cylinder and an inner hot Koch snowflake shaped cylinder as depicted in Figure 22.

Particular investigations have been done in order to show the effect of nanoparticles volume concentration ($\phi$=0, 2%, 3%, 4%, 5%, 8%) , Ra ($10^6 \geq Ra \geq 10^3$), Da ($10^{-2} \geq Da \geq 10^{-5}$) and Ha ($100 \geq Ha \geq 0$). In addition to geometrical parameters such as the undulation number (N = 1, 3, 5, and 9) and inner tube position. The investigations indicated above lead to the following findings:

1. When the Rayleigh number rises, the thermal performance intensifies and the flow field strengths in the enclosure.
2. During natural convection fluid flow and heat transfer, the most important parameter is Rayleigh number determining nature of fluid flow and the predominant heat transfer mode in the computational domain. Conduction heat transmission is dominant at low Ra values, whereas buoyancy-induced convection heat transfer takes over at high Ra numbers.
3. At low values of Hartmann number, the heat transfer is essentially diffusion dominated and the shape of the streamline tends to follow the geometry of the enclosure.
4. The magnetic field suppresses the flow in the enclosure thus it can serve as a flow controller.
5. While the average Nu number has an inverse relationship with the Ha number, it has a direct relationship with the Ra and Da numbers.

6. Ra, Da, and Ha considerably change the design of the streamlines and isotherms inside enclosure.
7. The effect of Hartmann number and Darcy number on heat transfer and Nusselt number increases noticeably at high convection strength.
8. The coupling of nanofluids with porous media has a high potential for heat transfer improvement in many thermal systems and provides many opportunities for systems development. This is owing to the greater surface area/volume of the porous medium and the improved features of the thermal properties of nanofluids.
9. Although adding nanoparticles may improve a fluid's thermal conductivity, doing so can also make it more viscous. Since convection is significantly influenced by viscosity, the impact of nanoparticles on improving thermal performance may be lessened as a consequence.
10. Due to the increased friction in a fluid, the formation of frictional entropy rises as the porosity of the medium increases.

# Future perspective

In the following section, some recommendations for future research work are presented to extend the present work potentially:

1. The majority of the presumptions established in this area of research are based on unrealistic constant boundary conditions, making them likely to contain inaccuracies when compared to experimental data.
2. Natural convection inside simple shapes of enclosures like rectangular and square geometries had been studied a lot. Thus, more unusual and complicated geometries should be taken into account in future research. Complex geometries include elements like blood cells, geometries with elastic walls, modern solar collectors, the food industry, heat exchangers, fuel cells, and microelectronic machinery.
3. Nusselt number and local total entropy generation are highly influenced by the inclination angle. Thus, the influences of inclination angles on fluid flow and heat transfer should be considered by researchers because it is quite useful in building and solar energy fields.
4. Type, size, and shape of nanoparticles also plays very important role in natural convection heat transfer enhancement. So incorporating their effect into the investigation of nanofluid natural convection is vital.
5. From a numerical point of view, nanofluids lead to a considerable increase in the heat transfer performance, which is in a good accordance with experimental results. Nonetheless, several improvements might be done to produce more accurate findings from numerical methods.
6. The effect of discrete and periodic heating and conjugate heat transfer, and the effect of variable magnetic field.
7. Future numerical investigations might be oriented toward radiation performance or boiling heat transfer of nanofluids.

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# Galerkin finite element analysis of thermal aspects of $Fe_3O_4$-MWCNT/water hybrid nanofluid filled in wavy enclosure with uniform magnetic field effect

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*Keywords:*
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ABSTRACT

In this contribution, a numerical investigation was made for heat transfer and steady magneto-hydrodynamic natural convection in a fined cold wavy-walled porous enclosure with a hot elliptic inner cylinder occupied by hybrid $Fe_3O_4$-MWCNT /water nanofluid. The enclosure is also placed in a uniform magnetic field. The governing equations are verified by using the Galerkin Finite Element Method (GFEM). Our numerical conclusions are expressed in terms of distributions of isotherms, Nusselt number, and streamlines, which are important, control parameters for the heat convection, and flow in the enclosure. The findings elucidate that the $Nu_{avg}$ rises with the growth of *Ra*, porosity ratio, and *Da* ratio increase, though it reduces with the growth of Hartmann number.

## 1. Introduction

The mastery of heat transfer is always sought out by researchers and engineers on the grounds of its extensive employment in industrial systems [1–6]. Knowing that the heat transfer improvement affected by several factors and the best convenient approach is to customize the thermal properties of the working fluid in a system for instance using nanofluid first established by Choi [7] which is fluid obtained by suspending a small dose of nanoparticles usually metal ones with a thermal conductivity with high-level in reference liquids which have weak thermal conductivity (ethylene glycol, $H_2O$ or oil).

Correspondingly, natural convection has been significantly studied in nanofluids within a cavity. The free convection was studied by Ghasemi [8] in a quadrilateral enclosure loaded with a $H_2O$-$Al_2O_3$ nanoliquid likewise Jahanshahi et al. [9] simulated the free convection using $H_2O$-$SiO_2$ nanoliquid the properties of this nanofluid were measured using an experimental setup. The results demonstrated that with the growth of the *Ra*, the $Nu_{avg}$ increases. However, it decreases whenever the *Ha* increases. Additionally, Ghasemi found that on account of the value of *Ra* and *Ha* numbers, the growth in the nanoparticles concentration may stimulate improvement or depreciation of the heat transfer rate. Other researchers added different shaped obstacles in the square cavity like Selimefendigil et al. [10] added square, diamond, and circular obstacles to study the impact of these obstacle forms on the flow behavior and the thermal performance. They observed deterioration in the heat transport rate when the obstacles are added at higher *Ra*. However, in the presence of these obstacles, it was observed that there was less deterioration in the mean Nusselt number when we raised the Hartmann number.

Sheikholeslami [11], Hussain [12], and Bararnia [13] performed studies where the added obstacles (rectangular; elliptic; triangular; circular; rhombic) in the square cavity are defined as heat sources as for the results they depicted that the $Nu_{avg}$ has a direct relation with nanoparticle concentration, *Ra* number and for the consequence of the shape of the obstacles it is determined that the best heat transfer is associated with using the triangular cylinder shape, other parameters have been investigated like the position of the inner elliptic heat source in Bararnia

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Review Article

# Recent advances on the applications of phase change materials for solar collectors, practical limitations, and challenges: A critical review

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ABSTRACT

Global warming is the most serious problem humanity faces in the twenty-first century. To avoid additional global warming, the world must transition away from fossil fuels and toward carbon-free energy sources such as solar energy. However, the current generation of solar collectors is incapable of fulfilling the worldwide need for energy supply, and new creative technologies are required to close the gap between solar energy production and demand. Phase change materials (PCM) are among the most effective and active fields of research in terms of long-term heat energy storage and thermal management. Due to their excellent properties, they can be coupled with solar collectors to conserve surplus solar energy and regulate the temperature of photovoltaic solar collectors. However, PCM's actual applications are limited due to their poor thermal conductivity, availability, cost, and various challenges. This review focuses on recent advancements in integrating PCMs into different types of solar collectors. Furthermore, it aims to detail numerous strategies as well as diverse improvement approaches and modifications that have been developed to improve the performance of PCMs incorporated into solar collectors. Finally, based on the thorough results of this analysis, future suggestions have been made to offer the researcher ideas and feasible concepts for future research into PCM/Solar collectors' system development.

## 1. Introduction

Humans have developed a reliance on many energy sources to sustain their civilized life. They are the only species capable of systematically harnessing energy external to their bodies, using the might of their intellect and a vast range of artifacts, ranging from basic tools to internal combustion engines and nuclear reactors [1]. Current energy production and consumption practices have impacted agriculture, industry, transportation, weaponry, communication, economics, urbanization, politics, and the environment [2–6]. That being said, the current world is facing an intensifying energy crisis as the international economy and population continue to grow, resulting in a massive increase in energy consumption. Apart from the fact that the majority of our energy requirements are supplied by fossil fuels such as coal, petrol, and natural gas, which not only wreak havoc on the environment by contributing to pollution and global warming, endangering life on our planet, but they are also quickly diminishing, posing a danger to future generations. As a result, mankind is forced to confront this energy crisis and transition to non-polluting renewable energy sources such as solar, ocean waves, wind, hydropower, and biomass. According to the Intergovernmental Panel on Climate Change (IPCC) projections, solar energy is likely the only renewable and pollution-free energy source with extractable and technical potential that surpasses our energy requirements in the future. Nowadays, solar energy is used in electricity production, heating, water treatment, air conditioning, and transportation [7–10].

Furthermore, the two methods of harnessing solar energy, photovoltaics and concentrating solar-thermal power, are becoming more affordable and efficient due to recent technological advancements [11–14]. Despite their impressive merits, they still suffer from many drawbacks, such as their intermittent nature, low efficiency, especially

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Research Papers

# Numerical investigation of a snowflake-shaped fin-assisted latent heat storage system using nanofluid

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FEM
PCM
Irregular domain

ABSTRACT

Latent heat thermal energy storage (LHTES) units can store important amounts of energy by employing phase change materials (PCMs). PCMs have a relatively inadequate thermal conductivity which hinders the thermal performance of LHTES. Thus, it is imperative to take measures to improve thermal conductivity or heat transfer within LHTES units. This article examines the heat diffusion improvement within wavy snowflake-shaped containers filled with nano-enhanced PCM (NEPCM). N-Octadecane enhanced with $Al_2O_3$ nanoparticles, respectively, are used as nanoparticles and PCM. A numerical model was developed using the standard Galerkin Finite Element Method to analyze the phase change phenomenon. The thermal performance of the LHTES is determined using thermodynamics' first and second laws. The effects of nanoparticle volume fractions ($\varphi$) and geometry parameters on the melting rate are investigated. The major findings revealed that the melting process could be well controlled using a lattice of heated fins. Also, the growth in waviness parameter and $\varphi$ enhances the rates of the heat transfer and average liquid fraction.

## 1. Introduction

The development and modernization of the societies ties to energy demand increase. Undoubtedly, heating systems and the discussion of their investigation have engaged the minds of researchers and have become the subject of their research [1–8]. Despite the high energy density of fossil fuels, their usage was limited by their side effect on the environment; in addition, the limited sources of fossil fuels and the resulting economic and political concerns caused turning into renewable energy sources an inevitable task. As reported by the energy outlook 2019 [9], renewable energy is considered the fastest-growing energy source and is estimated to provide a large portion of energy till 2040. Most renewable energy sources suffer from their inherent poor stability and uneven space-time distribution despite their benefits over traditional fossil energy sources. This shortcoming negatively affects renewable energy sources adaptation, including solar, wind, and tidal energy sources. In this situation, energy storage technologies are used to promote various renewable energies by solving this issue. To extend the utilization of solar thermal energy, thermal energy storage (TES) is used, which could be performed in three different ways [10]: sensible heat storage, latent heat storage and chemical, thermal energy storage. Considering the large required energy for phase change and the small temperature change during the phase change process [11], the latent thermal storage had drawn large attention of the researchers. The application of PCMs was studied in buildings [12], heat exchangers [13], solar water heating systems [14], air conditioning systems [15] and the automotive industry [16]. Although thermal energy storage and delivery could be performed by phase change from one phase to another, from the application point of view, the PCM with solid-liquid phase change is the most favorable [17]. Based on their phase change

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Research papers

# The numerical analysis of the melting process in a modified shell-and-tube phase change material heat storage system

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ABSTRACT

Thermal energy storage plays a major role in applying thermal energy sources such as waste heat and solar energy. As an efficient storage technique, the development of latent heat storage systems is a key factor for the successful application of thermal energy. This work presents thermal characteristics of a shell-and-tube phase change material (PCM) latent energy storage system with shell and tube forms of octagonal and three-lobe, respectively. The nano-enhanced paraffin wax was employed PCM, and the transient performance of the system was examined using the enthalpy-porosity method. The PCM temperature, melted fraction, and the Nusselt and Bejan numbers were adopted as system evaluation indexes, and sensitivity analysis was made to unveil the effect of copper nanoparticle (NP) concentration, the tube orientation angle and the eccentricity on system performance. The obtained results demonstrate that between the studied parameters, altering the eccentricity has the most effect on system characteristics; in the case of the above-located tube (denoted by case1), the melting time was reduced by 62 % compared to the base case. Changing the tube inclination angle and NP concentration does not show a significant effect on profiles of PCM temperature and melted fraction and mainly affect the Be number; using the case of 60° tube inclination angle and NP concentration of 4 % shows a slight improvement of temperature and melted fraction and reduces the average Be number.

## 1. Introduction

Optimization of heating systems for different purposes has always been one of the topics of interest to researchers, on which a lot of research has been done [1–5]. The topic of heat transfer and cooling and heating systems has always been involved with fluids, and this has led researchers to conduct research on fluid flow and heat transfer systems with fluid assistance [6–9]. In this regard, nanotechnology has made many contributions to the science of heat transfer as well as other engineering sciences and has made researchers in different fields of science work on different aspects of nanoscience [10,11]. The rapid expansion of civilization has increased the demand for fossil fuels [12]. The challenges and side-effects of employing fossil fuel sources such as environmental pollution and global warming resulted in switching to green and sustainable energy sources such as wind, solar, and hydrogen energy [13–15]. Solar energy is the most promising renewable energy source due to its abundance and relatively worldwide availability. However, due to the intermittent nature of solar energy, exploiting solar energy would be possible only through the development of energy storage technologies such as supercapacitors [16,17], lithium-based batteries [18–26], and thermal energy storage (TES) [27,28]. Energy storage in thermal energy storage (TES) systems could be made in sensible, latent and chemical forms in their respective suitable media. Latent thermal energy storage (LTES) is possible by exploiting the latent

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*Article*

# Numerical Simulations of Magnetohydrodynamics Natural Convection and Entropy Production in a Porous Annulus Bounded by Wavy Cylinder and Koch Snowflake Loaded with Cu–Water Nanofluid

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**Abstract:** The current paper presents a numerical study of the magnetohydrodynamics natural convection and entropy production of Cu–water nanofluid contained in a porous annulus between a heated Koch snowflake and wavy cylinder with lower temperature with respect to the Koch snowflake. The numerical algorithm is based on the Galerkin Finite Element Method. The impacts of Rayleigh number ($Ra = 10^3$, $10^4$, $10^5$, and $10^6$), Hartman number ($Ha$ = 0, 25, 50, and 100), Darcy number ($Da = 10^{-2}$, $10^{-3}$, $10^{-4}$, and $10^{-5}$), nanoparticle volumetric fraction ($\varphi$ = 2%, 3%, 4%, and 5%), and the undulations number of the outer wavy cylinder (three cases) on the distributions of isotherms, streamlines, mean Nusselt number ($Nu_{avg}$), as well as on total entropy production and Bejan number are thoroughly examined. The computational outcomes disclose that dispersing more Cu nanoparticles in the base fluid and creating a flow with higher intensity inside the annulus by raising the Rayleigh number bring about a boosted natural convective flow in the cavity, which improves the heat transmission rate. In addition, it can be noted that owing to the peculiar form of the heated Koch snowflake, nanofluid gets trapped between the angled parts, resulting in uneven temperature profiles with higher values in these places.

**Keywords:** magnetohydrodynamic; natural convection; Koch snowflake; hybrid nanofluid; porous media

## 1. Introduction

Convective heat transfer via a mix of materials has become an important technique in a range of industrial and residential applications, including building heating and cooling, thermal management of electronic components, systems of heat exchange, and solar energy. Several researchers have examined the characteristics of fluid flow and heat transmission in numerous technical applications [1–4]. In the last decade, high-conductivity nanoparticles have been presented as a means of enhancing heat transmission [5–8]. The dissolving of nanoparticles in the base fluid produces a fluid known as a nanofluid. An annular channel is one of the most significant concepts in thermal energy systems. They are used in a variety of heat and mass transfer technologies. Numerous researchers have examined the impact of geometric characteristics of the annulus, the thermophysical properties of the working fluid, such as nanofluids, and internal or external factors on free convective flow and heat transfer rate in numerous computational and experimental studies [9–14].

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# Numerical study on n-octadecane PCM melting process inside a pear-shaped finned container

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A R T I C L E I N F O

*Keywords:*
Nano-enhanced PCM
Latent heat thermal energy storage
$Al_2O_3$ nanoparticles
Fins
Melting process
Pear-shaped container

A B S T R A C T

This work numerically explores the melting process of a nano-enhanced phase change material (NePCM) in thermal energy storage (TES) system. The TES unit is pear-shaped and filled with n-octadecane PCM loaded with $Al_2O_3$ nanoparticles and fitted with copper fins. The heat transport governing equations are solved using the finite element method's enthalpy-porosity approach. The melting and heat transmission processes were investigated in terms of the impacts of a variety of factors, including the volume percentage of nanoparticles, the passage of time, the number and the dimensions of the fins. The findings show that the addition of nanoparticles improves the melting process of PCM. For example, adding 6% $Al_2O_3$ into PCM decreases the melting time by 12.5%. Furthermore, longer and thinner fins are advised to increase melting rate due to decreased thermal resistance enhanced heat propagation in the deeper regions of the thermal storage unit.

**Nomenclature**

*Abbreviations*

| | |
|---|---|
| PCM | phase change material |
| 2D | two-dimensional |
| C | Mushy zone morphology constant |
| LHTES | latent heat thermal energy storage |
| HTF | heat transfer fluid |
| NEPCM | nanoparticles enhanced PCM |

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# MHD natural convection of $Fe_3O_4$- MWCNT/ Water hybrid nanofluid filled in a porous annulus between a circular cylinder and Koch snowflake

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**KEYWORDS**

Magneto-hydrodynamic;
Natural convection;
Koch snowflake;
Hybrid nanofluid;
Porous media Galerkin finite element technique

**Abstract** In this work, the numerical investigation was conducted for the MHD natural convection and entropy generation characteristics of water-based hybrid nanofluid ($Fe_3O_4$-MWCNT) in a porous annulus between a cooled circular cylinder and a heated Koch snowflake subjected to a uniform magnetic force. The novelty of this work is presented by the special shape and different studied positions of the hot barrier. The governing equations are explained by employing the Finite Element Method. The impacts of nanoparticle volume fraction ($\varphi$ = 2 %, 3%,4%, and 5 %), Rayleigh number (Ra = $10^3$ to $10^6$), Hartman number (Ha = 0,25,50,100), Darcy number (Da = $10^{-2}$, $10^{-3}$, $10^{-4}$, and $10^{-5}$), and the position of the Koch snowflake (four cases) on the distributions of isotherms, streamlines, average Nusselt number ($Nu_{avg}$) as well as on total entropy generation and Bejan number are thoroughly examined. The computational outcomes indicate that increasing the Ra number is possible by changing the temperature between the hot and cold sources. By increasing this parameter, the buoyancy force of the fluid is strengthened. As the Da number increases, the penetration of the flow cross-section in the cavity increases, and the flow circulates

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Research Papers

# Thermal energy storage using nano phase change materials in corrugated plates heat exchangers with different geometries

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A R T I C L E I N F O

*Keywords:*
Nano-improved phase change material
Thermal energy storage
Heat exchanger
Corrugated channel
PCM melting
2D solution

A B S T R A C T

This manuscript investigates the thermal energy storage of nano-improved phase change material (NIPCM) used in a corrugated or undulated channel in heat exchangers. The problem is solved in two dimensions. The solution of the equations system is obtained by the Galerkin finite element method, and the enthalpy analysis is also performed. Flat, sinusoidal waves, square waves, triangular waves, and sawtooth wave profiles are considered different geometries of the plates. The impacts of Reynolds number ($Re$ = 500–2000), inlet temperature (T = 65–80 °C), and nanoparticle volume fraction (φ = 0–8 %) on the thermal performance of heat exchangers are also investigated. The heat transfer fluid (HTF) between the plates is water, while the shell is filled with NIPCM (Cu-Paraffin). As the main outcome, the sinusoidal wave profile had the maximum average temperature and entropy, among other cases. Out of all the cases that were examined, the sawtooth plate had the best performance. At the highest values of $Re$, tin, and ϕ, the sawtooth plate reduced the melting time by 12 %, 11 % and 12 % compared to the flat plate, respectively.

## 1. Introduction

Thermal energy storage is gaining popularity in energy-efficient and reliable systems. Along with classic thermal storage technologies, latent heat storage (LHS) is becoming more prevalent in commercial applications. Recent years have seen an exponential increase in the number of investigations devoted to such phase change material (PCM)-based systems. Numerous studies have demonstrated the importance of improving the quality and amount of heat recuperated from PCM heat storage systems. Some studies have concentrated on PCM's cooling and heating capacities in various domestic and industrial applications including solar systems [1–4], heat exchanger [5–7], thermal management systems [8,9] heat recovery [10,11], photovoltaic systems [12,13], energy storage units [14,15]. Zhou et al. [16] researched the use of heat storage in a solar water heater. They reported that using the phase transition material boosted the solar fraction significantly. Bazri et al. [17] analyzed the function of PCM integrated with a solar water heater (SWH). The evacuated tube arrays for the heat pipe were loaded with paraffin to increase the heat transmission rate throughout the night and linked to the storage tank. The authors discovered that the system's energy productivity ranged from 32 to 42 % on days with low solar intensity when PCM was used. Wu et al. [18] inspected the PCM impact and oscillating heat pipes on the thermal efficiency of an SWH. In China, full-year measurements have been taken for two years in a row. They discovered that when utilizing PCM to heat the outlet water in an SWH, the outlet water temperature was sustained above 50 °C throughout the summer night. Huang et al. [19] explored the impact of PCM placements on solar water stratification characteristics. During studies, varied volume flow rates of 0.06, 0.18, 0.3, 0.42, and 0.54 $m^3$/h were investigated. The findings of the study indicated that optimum stratification occurs when PCM is installed at the bottom of the hot water storage tank, and the incoming flow rate exceeds 0.42 $m^3$/h. Flow rates, phase transition temperature, water intake temperature, flow gap, and PCM plate thickness are all critical parameters in the engineering of water-PCM heat exchanger systems. Akyol et al. [20] explored an air-PCM system utilized in natural cooling systems numerically and experimentally. Their findings indicate that the air input temperature and velocity significantly influence the cooling effectiveness of the air-PCM system.

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RESEARCH ARTICLE

# Partial velocity slip effect on working magneto non-Newtonian nanofluids flow in solar collectors subject to change viscosity and thermal conductivity with temperature

**Wasim Jamshed[1]*, Mohamed R. Eid[2,3], Abederrahmane Aissa[4], Abed Mourad[4], Kottakkaran Sooppy Nisar[5], Faisal Shahzad[1], C. Ahamed Saleel[6], V. Vijayakumar[7]**

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## Abstract

Solar thermal collectors distribute, capture, and transform the solar energy into a solar thermal concentration device. The present paper provides a mathematical model for analyzing the flow characteristics and transport of heat to solar collectors (SCs) from non-Newtonian nanofluids. The non-Newtonian power-law scheme is considered for the nanofluid through partial slip constraints at the boundary of a porous flat surface. The nanofluid is assumed to differ in viscosity and thermal conductivity linearly with temperature changes and the magnetic field is appliqued to the stream in the transverse direction. The method of similarity conversion is used to convert the governing structure of partial differential formulas into the system of ordinary differential ones. Using the Keller box procedure, the outcoming ordinary differential formulas along with partial slip constraints are numerically resolved. A discussion on the flowing and heat transport characteristics of nanofluid influenced by power law index, Joule heating parameter, MHD parameter and slip parameters are included from a physical point of view. Comparison of temperature profiles showed a marked temperature increase in the boundary layer due to Joule heating. The thickness of the motion boundary-layer is minimized and the transport of heat through boundary-layer is improved with the partial slip velocity and magnetic parameters rising. Finally, With an increase in the Eckert number, the distribution of temperature within boundary layer is increased.

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# A Numerical Investigation of a Melting Rate Enhancement inside a Thermal Energy Storage System of Finned Heat Pipe with Nano-Enhanced Phase Change Material

**Anuwat Jirawattanapanit [1,†], Aissa Abderrahmane [2], Abe Mourad [2], Kamel Guedri [3], Obai Younis [4], Belgacem Bouallegue [5], Khanyaluck Subkrajang [6,*], Grienggrai Rajchakit [7] and Nehad Ali Shah [8,†]**

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**Abstract:** Thermal energy storage via the use of latent heat and phase transition materials is a popular technology in energy storage systems. It is vital to research different thermal enhancement techniques to further improve phase transition materials' weak thermal conductivity in these systems. This work addresses the creation of a basic shell and a tube thermal storage device with wavy outer walls. Then, two key methods for thermal augmentation are discussed: fins and the use of a nano-enhanced phase change material (NePCM). Using the enthalpy–porosity methodology, a numerical model is developed to highlight the viability of designing such a model utilizing reduced assumptions, both for engineering considerations and real-time predictive control methods. Different concentrations of copper nanoparticles (0, 2, and 4 vol%) and wavenumbers (4,6 and 8) are investigated in order to obtain the best heat transmission and acceleration of the melting process. The time required to reach total melting in the studied TES system is reduced by 14% and 31% in the examined TES system, respectively, when NePCM (4 vol% nanoparticles) and N = 8 are used instead of pure PCM and N = 4. The finding from this investigation could be used to design a shell-and-tube base thermal energy storage unit.

**Keywords:** shell-and-tube TES; nano-enhanced PCM; nanoparticles; fins; latent heat thermal energy storage (LHTES)

## 1. Introduction

Energy consumption continues to rise year after year as a result of rising worldwide demand, as shown by data released by International Energy Agencies [1,2]. Increased energy use from conventional energy sources such as fossil fuels, on the other hand, is both unsustainable and very detrimental to the environment. To address rising energy demand, researchers have focused on the need to develop clean and renewable energy sources and associated technologies [3–5]. In recent years, solutions such as the use of better fluids and energy storage devices have been investigated [6–9]. Thermal energy storage (TES) is a

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# Natural Convection within Inversed T-Shaped Enclosure Filled by Nano-Enhanced Phase Change Material: Numerical Investigation

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**Abstract:** Energy saving has always been a topic of great interest. The usage of nano-enhanced phase change material NePCM is one of the energy-saving methods that has gained increasing interest. In the current report, we intend to simulate the natural convection flow of NePCM inside an inverse T-shaped enclosure. The complex nature of the flow results from the following factors: the enclosure contains a hot trapezoidal fin on the bottom wall, the enclosure is saturated with pours media, and it is exposed to a magnetic field. The governing equations of the studied system are numerically addressed by the higher order Galerkin finite element method (GFEM). The impacts of the Darcy number (Da = $10^{-2}$–$10^{-5}$), Rayleigh number (Ra = $10^3$–$10^6$), nanoparticle volume fraction (φ = 0–0.08), and Hartmann number (Ha = 0–100) are analyzed. The results indicate that both local and average Nusselt numbers were considerably affected by Ra and Da values, while the influence of other parameters was negligible. Increasing Ra (increasing buoyancy force) from $10^3$ to $10^6$ enhanced the maximum average Nusselt number by 740%, while increasing Da (increasing the permeability) from $10^{-5}$ to $10^{-2}$ enhanced both the maximum average Nusselt number and the maximum local Nusselt number by the same rate (360%).

**Keywords:** magnetohydrodynamics; inversed T-shaped enclosure; NEPCM; natural convection; nanofluid

## 1. Introduction

In the last several decades, the heat transport of nanofluids in various shapes with varying outset and boundary conditions has been a popular research point. This is explained by the fact that these geometries have been widely used in real-world applications, such as building thermal management, electronic device cooling, biochemical and food processing, and renewable energy applications [1–7]. Raizah et al. [8] examined nanofluid natural convection (NC) flow inside a V-shaped cavity saturated with porous media. The findings showed that the best-case scenario for porous media is a horizontal heterogeneous porous medium. The buoyancy force is augmented with a Rayleigh number increase,

*nanomaterials*

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*Article*

# Enhancing the Melting Process of Shell-and-Tube PCM Thermal Energy Storage Unit Using Modified Tube Design

**Aissa Abderrahmane [1], Naef A. A. Qasem [2], Abed Mourad [1], Mohammad Al-Khaleel [3,4,*], Zafar Said [5,6], Kamel Guedri [7], Obai Younis [8,9] and Riadh Marzouki [10,11]**

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**Abstract:** Recently, phase change materials (PCMs) have gained great attention from engineers and researchers due to their exceptional properties for thermal energy storing, which would effectively aid in reducing carbon footprint and support the global transition of using renewable energy. The current research attempts to enhance the thermal performance of a shell-and-tube heat exchanger by means of using PCM and a modified tube design. The enthalpy–porosity method is employed for modelling the phase change. Paraffin wax is treated as PCM and poured within the annulus; the annulus comprises a circular shell and a fined wavy (trefoil-shaped) tube. In addition, copper nanoparticles are incorporated with the base PCM to enhance the thermal conductivity and melting rate. Effects of many factors, including nanoparticle concentration, the orientation of the interior wavy tube, and the fin length, were examined. Results obtained from the current model imply that Cu nanoparticles added to PCM materials improve thermal and melting properties while reducing entropy formation. The highest results (27% decrease in melting time) are obtained when a concentration of nanoparticles of 8% is used. Additionally, the fins' location is critical because fins with 45° inclination could achieve a 50% expedition in the melting process.

**Keywords:** shell-and-tube TES; nano-enhanced PCM; nanoparticles; fins; latent heat energy storage

## 1. Introduction

Energy storage will play an increasingly important role in the energy supply chain. The adoption of various thermal energy storage (TES) technologies is projected to increase, given that thermal energy accounts for a significant amount of overall energy consumption. In this framework, the past decade has seen a surge in research on latent heat thermal energy storage (LHTES) employing phase change materials (PCMs). A significant quantity of heat is absorbed/released during a material's phase shift. This opens significant

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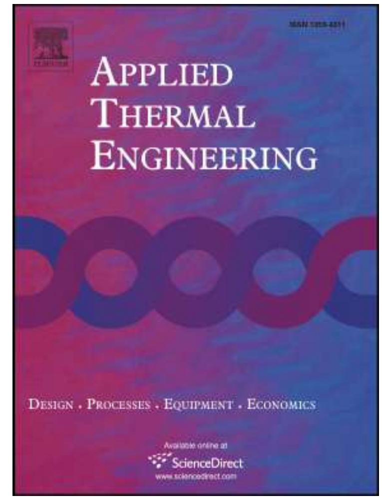


A Review of the Enhancement of Solar Thermal Collectors using Nanofluids and Turbulators

Aissa Abderrahmane, Naef A.A.Qasem, Abed Mourad, Houssem Laidoudi, Obai Younis, Kamel Guerdi, Anas Alazzam

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# Second law analysis of a 3D magnetic buoyancy-driven flow of hybrid nanofluid inside a wavy cubical cavity partially filled with porous layer and non-Newtonian layer

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ABSTRACT

The current paper presents numerical results of the 3D buoyancy-driven flow of a hybrid nanofluid in a cubical cavity in the presence of a magnetic field. The computational domain comprises two layers: a non-Newtonian fluid layer and a hybrid nanofluid layer. The temperature disparity within the domain results from heating the wavy bottom wall and cooling both sidewalls while the top wall is insulated. A magnetic field is applied on the positive z-axis. To encounter the non-Newtonian layer influence, the power-law model is considered. The solution of the governing equations is obtained by the Galerkin FEM method. The effects of geometrical parameters of the problem are discussed and illustrated. The results indicate that by simultaneously using non-Newtonian $Fe_3O_4$/MWCNT hybrid nanofluid and porous media, the heat exchange in the 3-D cavity is positively affected by the growth in Rayleigh number, Darcy number as well as the height of the porous layer. Furthermore, it is negatively affected by the rise of the magnetic field, corrugation number, and a minor degree when the flow index n was increased due to the pseudo-plastic fluid's high viscosity and shear force.

*Abbreviations*

| | |
|---|---|
| H | Height of the outer and inner conical (m) |
| Nu | Nusselt number |
| P | Dimensionless pressure |
| Pr | Prandtl number |
| Ra | Rayleigh number |
| X, Y | Dimensionless coordinate |
| T | Temperature (K) |
| u | Velocity in the x-direction $\left(\frac{m}{s}\right)$ |
| v | Velocity in the y-direction (m/s) |
| U, V | Dimensionless velocity |

*Greek symbols*

| | |
|---|---|
| a | Thermal diffusivity $(m^2/s)$ |
| $B$ | Coefficient of thermal expansion (1/K) |
| $\theta$ | Dimensionless temperature |
| $\rho$ | Fluid density $(kg/m^3)$ |
| v | Kinematic viscosity $(m^2/s)$ |
| $\mu$ | Dynamic viscosity (kg/ms) |
| k | Fluid thermal conductivity (w/m K) |

## 1. Introduction

Fluid is one of the most important requirements of materials that have many applications and the role of fluids is undeniable in various industries and applications. In this regard, researchers tried to research

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Regular Article

# Effect of double rotating cylinders on the MHD mixed convection and entropy generation of a 3D cubic enclosure filled by nano-PCM

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**Abstract** In this manuscript, phase change material (PCM) including the nanoparticles is considered in a 3D cubic enclosure to investigate the mixed convection of heat transfer under the magnetic field effect. Double rotating cylinders also are located in the middle of the enclosure to study the effect of their angular velocity in different conditions. Governing equations are solved by Galerkin Finite Element Method (GFEM) and were confirmed by previous studies. As main outcomes, results with enhanced angular velocity, both the average temperature and cumulative energy were significantly decreased. Furthermore, unaltered fluidity (Ha = 0) imposes greater entropy, but this tendency reverses when the Hartman number (Ha) rises, resulting in minimum entropy trends.

## Nomenclature

| | |
|---|---|
| r | Radius of the cylinder, [m] |
| h | Dimensional length of the heated wall (m) |
| p | Static pressure ($N/m^2$) |
| Pr | Prandtl number |
| X,Y | Dimensionless coordinate |
| T | Local temperature ($^\circ$K) |
| u | Velocity in the x-direction (m/s) |
| v | Velocity in the y-direction (m/s) |
| U,V | Dimensionless velocity |
| $C_{ps}$ | solid PCM-specific heat (kJ/kgK) |
| $C_{pl}$ | liquid PCM-specific heat (kJ/kgK) |
| L | latent heat of fusion of the PCM (kJ/kg) |
| $T_m$ | PCM melting temperature (K) |

## Greek symbols

| | |
|---|---|
| α | Thermal diffusivity ($m^2/s$) |
| $\beta$ | Coefficient of thermal expansion (1/°K) |
| $\theta$ | Dimensionless temperature |
| $k_{ls}$ | solid PCM thermal conductivity ($W/m \cdot K$) |
| $k_l$ | liquid PCM thermal conductivity ($W/m \cdot K$) |
| $\rho_l$ | liquid PCM density ($kg/m^3$) |
| $\rho_s$ | solid PCM density ($kg/m^3$) |
| ν | Kinematic viscosity ($m^2/s$) |
| μ | Dynamic viscosity (kg/ms) |
| Ω | angular rotational speed of the cylinder, [rad/s] |

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## 1 INTRODUCTION

PCM is an abbreviation of phase change materials, which is a substance that releases/absorbs enough energy to provide useful heat/cooling at the phase transition. As compared to sensible heat storage, a PCM is capable of storing and releasing large amounts of energy by melting and solidifying at the phase change temperature. These capabilities make PCMs present across a broad spectrum of heat transfer applications, such as solar collectors, where the PCM is embedded to store surplus heat for later use [1]. Abdollahi and Rahimi [2] surveyed the experimental effects of employing Boehmite nanofluid on the performance of a hybrid PV/PCM system. According to the results, utilizing PCM and nanofluid cooled the PV cell and increased the electrical efficiency by up to 58.80%. Kabeel et al. [3] enhanced the efficiency of stepped solar stills by employing PCM and graphite as hybrid storage materials in addition to internal reflectors. The percentage improvement in the daily efficiency was recorded

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# MHD Hybrid Nanofluid Mixed Convection Heat Transfer and Entropy Generation in a 3-D Triangular Porous Cavity with Zigzag Wall and Rotating Cylinder

**Aissa Abderrahmane [1,†], Naef A. A. Qasem [2], Obai Younis [3,4], Riadh Marzouki [5], Abed Mourad [1], Nehad Ali Shah [6,*,†] and Jae Dong Chung [6]**

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**Abstract:** The purpose of this work was to conduct a numerical examination of mixed convective heat transfer in a three-dimensional triangular enclosure with a revolving circular cylinder in the cavity's center. Numerical simulations of the hybrid $Fe_3O_4$/MWCNT-water nanofluid are performed using the finite element approach (FEM). The simulation is carried out for a range of parameter values, including the Darcy number (between $10^{-5}$ and $10^{-2}$), the Hartmann number (between 0 and 100), the angular speed of the rotation (between −500 and 1000), and the number of zigzags. The stream function, isotherms, and isentropic contours illustrate the impact of many parameters on motion, heat transfer, and entropy formation. The findings indicate that for enhancing the heat transfer rates of hybrid nanofluid in a three-dimensional triangular porous cavity fitted with a rotating cylinder and subjected to a magnetic field, Darcy number > $10^{-3}$, Hartmann number < 0, one zigzag on the hot surface, and rotation speed >500 in flow direction are recommended.

**Keywords:** zigzag; nanoliquid; FEM; porous; MHD

**MSC:** 76D05; 80A05; 80M10

## 1. Introduction

Nanofluids are a unique type of artificial fluid that incorporate nanoparticles. The unique and original properties of nanofluids that encourage us to use it instead of ordinary liquids as a coolant are its greater thermal conductivity and enhanced heat transmission capabilities. Heat pipes, solar receivers, petroleum exploration, chemical engineering, electronics cooling, mechanical engineering, and solar collectors are just a few of the key technologies that can utilize nanofluids to improve their performance [1–3]. Suspending nanoparticles in traditional working fluids has been shown to boost heat transfer rates by growing thermal conductivity. Nevertheless, the magnitude of the increment in heat transmission stated in the literature varies greatly. Numerous research articles (both experimental and computational) on application of nanofluids in various fields have been published [4–8].

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# Melting enhancement of PCM in a finned tube latent heat thermal energy storage

Sameh Ahmed[1,2,9], Aissa Abderrahmane[3], Abdulkafi Mohammed Saeed[4], Kamel Guedri[5], Abed Mourad[3], Obai Younes[6], Thongchai Botmart[7]✉ & Nehad Ali Shah[8,9]

**The current paper discusses the numerical simulation results of the NePCM melting process inside an annulus thermal storage system. The TES system consists of a wavy shell wall and a cylindrical tube equipped with three fins. The enthalpy-porosity method was utilized to address the transient behavior of the melting process, while the Galerkin FE technique was used to solve the system governing equations. The results were displayed for different inner tube positions (right-left–up and down), inner cylinder rotation angle ($0 \leq \alpha \leq 3\pi/2$), and the nano-additives concentration ($0 \leq \phi \leq 0.04$). The findings indicated that high values of nano-additives concentration (0.4), bigger values of tube rotation angle ($3\pi/2$), and location of the tube at the lower position accelerated the NePCM melting process.**

**Abbreviations**

| | |
|---|---|
| g | Gravity |
| $T_m$ | Fusion temperature |
| C | Mushy zone constant |
| NEPCM | Nanoenhanced PCM |
| $L_f$ | Latent heat coefficient |
| k | Thermal conductivity |
| $T_s$ | Solidus temperature |
| FEM | Finite element method |
| $T_l$ | Liquidus temperature |

**Greek symbols**

| | |
|---|---|
| $a$ | Thermal diffusivity ($m^2/s$) |
| $\rho$ | Fluid density |
| $\phi$ | Nanoparticle volume fraction |

**Subscripts**

| | |
|---|---|
| $nf$ | NEPCM |
| $f$ | Pure fluid |

Energy storage is critical in thermal systems that use intermittent energy sources such as solar energy. Although less difficult, sensible heat storage needs large volumes to store the storage material and also exhibits temperature change throughout the charge/discharge cycles[1,2]. On the other hand, latent heat thermal energy storage (LHTES) systems have a large thermal heat capacity, high energy storage density, negligible temperature change throughout

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# MHD darcy-forchheimer nanofluid flow and entropy optimization in an odd-shaped enclosure filled with a (MWCNT-$Fe_3O_4$/water) using galerkin finite element analysis

Wael Al-Kouz[1]✉, Abderrahmane Aissa[2], Aimad Koulali[2], Wasim Jamshed[3], Hazim Moria[4], Kottakkaran Sooppy Nisar[5], Abed Mourad[2], Abdel-Haleem Abdel-Aty[6,7], M. Motawi Khashan[8] & I. S. Yahia[9,10,11]

**MHD nanoliquid convective flow in an odd-shaped cavity filled with a multi-walled carbon nanotube-iron (II, III) oxide (MWCNT-$Fe_3O_4$) hybrid nanofluid is reported. The side walls are adiabatic, and the internal and external borders of the cavity are isothermally kept at high and low temperatures of Th and Tc, respectively. The governing equations obtained with the Boussinesq approximation are solved using Galerkin Finite Element Method (GFEM). Impact of Darcy number (Da), Hartmann number (Ha), Rayleigh number (Ra), solid volume fraction (ϕ), and Heated-wall length effect are presented. Outputs are illustrated in forms of streamlines, isotherms, and Nusselt number. The impact of multiple parameters namely Rayleigh number, Darcy number, on entropy generation rate was analyzed and discussed in post-processing under laminar and turbulent flow regimes.**

**Abbreviations**

| | |
|---|---|
| h | Dimensional length of the heated wall (m) |
| H | Height of the outer and inner conical (m) |
| Nu | Nusselt number |
| p | Static pressure ($N/m^2$) |
| P | Dimensionless pressure |
| Pr | Prandtl number |
| Ra | Rayleigh number |
| X,Y | Dimensionless coordinate |
| T | Local temperature (°K) |
| u | Velocity in the x direction (m/s) |

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# Galerkin finite element analysis of magneto two-phase nanofluid flowing in double wavy enclosure comprehending an adiabatic rotating cylinder

Wael Al-Kouz[1], Bilal Abdel-Illah Bendrer[2], Abderrahmane Aissa[2], Ahmad Almuhtady[1], Wasim Jamshed[3]✉, Kottakkaran Sooppy Nisar[4], Abed Mourad[2], Nawal A. Alshehri[5] & Mohammed Zakarya[6,7]

**In this work, the finite element method is employed to simulate heat transfer and irreversibilities in a mixed convection two-phase flow through a wavy enclosure filled with water–alumina nanoliquid and contains a rotating solid cylinder in the presence of a uniform magnetic field. Impact of the variations of undulations number ($0 \le N \le 5$), Ra ($10^3 \le Ra \le 10^6$), Ha ($0 \le Ha \le 100$), and angular rotational velocity ($-500 \le \Omega \le 500$) were presented. Isotherms distribution, streamlines and isentropic lines are displayed. The governing equations are verified by using the Galerkin Finite Element Method (GFEM). The Nusselt numbers are calculated and displayed graphically for several parametric studies. The computational calculations were carried out using Buongiorno's non-homogeneous model. To illustrate the studied problem, a thorough discussion of the findings was conducted. The results show the enhacement of the maximum value of the flow function and the heat transfer process by increasing the value of Rayleigh number. Furthermore the irreversibility is primarily governed by the heat transfer component and the increment of the waviness of the active surfaces or the cylinder rotational velocity or hartmann number will suppress the fluid motion and hinders the heat transfer process.**

In recent years, enhancement of the heat transfer in industrial systems and engineering in general has become one of the most significant challenges of the twenty-first century[1–4]. Therefore, it is necessary to utilize modern technologies to overcome the problems and hindrances that limit the heat transfer process, different techniques can be employed to achieve this objective namely nanofluids, porous medium, magnetic fields, irregular walls, etc.

Nanofluid technologies are at the center of the interest of many investigators since their thermal conductivities are higher than conventional heat transfer fluids[4–7]. They present a very exciting advantage as they enable the enhancement of heat transfer rate of a thermal system without a single change to any of its components, and this can come about by simply suspending an iota of nanoparticles in a base fluid such as ethylene glycol, oil, and water. they have been used for the first time by Choi[8] in 1995, since then many studies have been carried out to investigate their flow patterns and thermal behavior. Numerical research was conducted by Khanafer et al.[9] to analyze the buoyancy-driven convection improvement of nanofluids in a 2D enclosure. Their outcomes explored that the nanoliquid thermal performance rate improves with an improvement in the solid concentration, the same model was adopted by Jou and Tzeng[10] to examine the performance of nanoliquid heat transfer inside a rectangular cavity. Their results show that an increase in heat transfer rate is critical for nanofluids than pure fluids. Masoud et al.[11] investigate natural convection in horizontal concentric annuli using different types of

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# Analysis of mixed convection of a power-law non-Newtonian nanofluid through a vented enclosure with rotating cylinder under magnetic field

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ABSTRACT

The impact of an inner adiabatic rotating cylinder within a vented cavity on the mixed convection of a hybrid nanofluid is investigated in this paper using a numerical solution. The governing equations of mixed convection motion are assumed to be two-dimensional, steady, and laminar for an incompressible power-law non-Newtonian hybrid nanofluid. Using the finite element technique, these equations are numerically solved. ($Al_2O_3$–Cu/CMC) is presented as a nanofluid in this study. The effects of significant parameters such as the Hartman number ($0 < Ha < 100$), cylinder radii ($0.1 < R < 0.25$), cylinder positions ($0.25 < AR < 0.75$), angular rotational speed ($-10 \leq \Omega \leq 10$), Grashof number ($10^3 \leq Gr \leq 10^5$) and Reynolds number ($50 \leq Re \leq 500$) are studied. The gathered information is displayed using a variety of qualitative and quantitative numbers. The findings report that rotating the stationary cylinder counterclockwise enhances convective heat transfer, whereas rotating it clockwise has the opposite effect. Furthermore, when the cylinder is rotated counterclockwise, the heat transfer improves as the cylinder approaches the hot wall.

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## 1. Introduction

Currently, energy is the most important commodity for humankind, with its various forms; it is the basis of our modern world technology and industry. Furthermore, it is known that most of our energy resources are finite, and collecting them is harmful to our environment (Han, 2021; Shamshuddin et al., 2021; Al-Kouz et al., 2021); which makes energy savings an important endeavor for many governments. Consequently, countless researchers have approached this challenge, and different studies were carried out on the energy issue (Radouane et al., 2020; Sadeghian et al., 2021; Ahmed, et al., 2016; Medebber et al., 2019). In addition to energy, researchers turned to nanotechnology, and nanotechnology led to many advances in various fields of engineering and other sciences, and it can be said that a lot of research in this field is focused on the last two decades (Bilal et al., 2021; Farahmandjou et al., 2021; Guo et al., 2021; Liu et al., 2021; Shen et al., 2022; Xin et al., 2022; Xu et al., 2021; Zahmatkesh et al., 2021). One of the most significant efforts in this endeavor is enhancing the fluid flow performance and heat transfer processes. This issue has been one of the important challenges of researchers in recent years (Athiyaman and Magapa, 2019; Chen et al., 2022; Eldo et al., 2019; Zhang et al., 2022a,b). Accordingly, different approaches were developed. Research on increasing thermal conductivity and reducing viscosity has always been of interest to researchers (Bai, 2022). One of the most recent is nanofluids, a new class of thermal fluids first put forward by a team of researchers led by Choi (Choi, 1995). They developed an engineering technique in which nanoparticles are suspended in a conventional thermal fluid to improve the thermal conductivity of the latter, which in turn recovers the heat transfer rate. (Slimani et al., 2020; Waini et al., 2022; Khan et al., 2022; Khan et al., 2021; Gholami et al., 2018;

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Review article

# Hemispherical solar still: Recent advances and development

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A B S T R A C T

Approximately (97 percent) of the water on Earth is salty or polluted, leaving just 3% as freshwater, only about (1%) of which is easily accessible for human use. The world's population is increasingly dependent on this priceless resource for electricity, irrigation, industrial processes, and everyday use. Solar desalination is gaining prominence as the most viable method for addressing water shortage in all elements of sustainable development. Several solar distillations processes use various strategies to create clean water. The hemispherical solar still (HSS) is one of the most effective alternatives for meeting the need for freshwater in rural and distant locations However, there are limits to the performance of hemispherical solar stills, and various researchers have examined the ability to enhance (HSS) thermal performance. This comprehensive review analyses and reports on the design and operating characteristics that impact the performance of the (HSS). Generally, hemispherical solar still has relatively better thermal performance than other types of solar stills. The maximum solar radiation, daily accumulative yield, thermal efficiency, CPL and recovery period for different studies related to (HSS) are prepared and arranged carefully in the present work. Additionally, the cost analysis was also considered. In order to help the researchers understand the developments of (HSSs), the most important findings of the reviewed papers were summarized.

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RESEARCH ARTICLE

# The performance enhancement of solar cooker integrated with photovoltaic module and evacuated tubes using ZnO/Acalypha Indica leaf extract: response surface study analysis

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**Abstract**

In this study, the effect of employing ZnO/Acalypha Indica leaf extract (ZAE) on the energy absorption of a coated portable solar cooker has been examined using an experimental setup. A prototypical model has been developed to corroborate in associating an investigative outcome per constituents of the experiments. The studied heat transfer process in ZAE is stable for harsh conditions. The design analysis and an estimation of the system performance were done given various parameters including the pressure of the vacuum envelope, bar plate coating digestion, emissivity, and solar rays. The fabricated solar was tested with and without ZAE to investigate the impact of this coating material on the solar cooker's thermal performance. To observe the performance of the new design, two figures of merit ($F_1$ and $F_2$) have been introduced. The factual food cooking assessments were for a family of four people, which operated in ZAE coating (0.8, 1.0, 1.2 µm) of the solar cooker. The values of $F_1$ and $F_2$ for the proposed cooker were obtained as 0.1520 and 0.4235, respectively, which is intact with the BIS values. The results revealed that employing ZAE instead of a thermal NHC-PV solar cooker reduced the time required to boil 2 L of water for about 47 min. The overall thermal energy productivity of the solar cooker with electrical backup was obtained as 42.65%, indicating that the ZAE coating can improve the thermal efficiency by 10.35%.

**Keywords** Electrical backup · Evacuated tubes · Photovoltaic panel · Thermal model · Solar cooker

## Introduction

A solar cooking process is a method in which solar radiation is utilized to naturally cook substances. Research worldwide have found out that solar cookers have sustainability for cooking in rural and urban areas with reduced energy consumption. A solar cooker using sun radiation as a heat source, can be utilized on hot sunny days, but on rainy and winter days, it is useless. It has been found that a solar cooker with an electrical backup will overcome these inconveniences. An electric backup integrated with a solar cooker has shown better performance compared to the cooker supported with thermal energy alone. Moreover, selectively coated absorbers using nanoparticles play an important role in enhancing the performance of solar cookers. Several studies have assessed the effect of selective absorber coating using nanoparticles. Kaiyan et al. (2009) used a light funnel to congregate solar energy to achieve temperature suitable for industrial and domestic usage. It was identified that a temperature of 250 °C is achieved with a lighting area of 1.5 $m^2$. Prasanna and Umanand (2011) experimented by transferring solar energy to the kitchen using fluid circulation to stimulate a cooker using the concept of maximum power point tracking (MPPT) for a thermal collector. Javadi et al. (2013) also reviewed the effect of using nanofluids on the performance of solar collectors. In their review, care was taken to highlight the impact of two-phase analysis of the nanofluid with more than one nanoparticle in the heat transfer fluid. Hussein et al. (2017) reviewed theoretical, numerical, and experimental studies of a heat pipe solar

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RESEARCH ARTICLE

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# Thermal analysis on Darcy-Forchheimer swirling Casson hybrid nanofluid flow inside parallel plates in parabolic trough solar collector: An application to solar aircraft

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**Summary**

As a try, this work has been focused in the way towards the effective contribution in the field of solar aviation using renowned nanotechnology. After realizing the causes and effects of traditionally used energy forms, the search of cost-efficient, eco-friendly, and most prominent renewable source leads us back to the solar utilities. Research era of solar radiation-powered aircraft has been in trend. Focusing on that, an efficient numerical model representing the flow and thermal aspects of a parabolic trough surface collector (PTSC) embedded on solar aircraft wings has been adopted for this study. As the first time with the note, an eminent and leading form of thermal efficient fluid of kind, the Casson hybrid nanofluid has been engaged with the expectations of enhanced performance in the solar aircraft wings. To test it, a trending reputable numerical scheme of the Keller-box method has been utilized and the parametrical studies were carried out. The upshots of those studies provide the affable proofs in favor of our expectations towards the improved solar wings with better thermal efficiency. The glimpse of those successes in the parametrical level has been showcased in the forms of tables and graphs. The lateral "x" direction significant about the inertial forces, suspended particle ratio, and skin resistance phenomena, while for the transverse fluidity in the "y" direction were has to be concern about the magnetic interactions, rotational coordinates, viscous nature of the fluid along with the porous states. The power of hybrid nanofluid combos was exposed in higher notes in a unique state of solar aircraft wings. Furthermore, the thermal efficiency of hybrid nanofluids over nanofluids got down to a minimal level of 6.1% and peaked up to 21.8%.

**KEYWORDS**

Casson hybrid nanofluid, Keller-box method, Lorentz force, rotating flow, viscous dissipation

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Regular Article

# Natural convection of nanoliquid from elliptic cylinder in wavy enclosure under the effect of uniform magnetic field: numerical investigation

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**Abstract** In the current article, a three-dimensional numerical simulation is conducted to scrutinize the steady laminar natural convective flow and transfer of heat between a cold wavy porous enclosure and a hot elliptic cylinder. Alumina nanoparticles are dispersed in the water to enhance the heat exchange process. The nanofluid flow is taken as laminar and incompressible, while the advection inertia effect in the porous layer is taken into account by adopting the Darcy–Forchheimer model. The problem is explained in the dimensionless form of the governing equations and solved by the finite element method. The influences of different governing parameters such as nanoparticles volume fraction ($\phi$), angle of rotation ($\alpha$), Darcy number (Da), Hartmann number (Ha), and Rayleigh number (Ra) on the fluid flow, temperature ($T$) filed and average Nusselt number are presented. The results exhibit that the heat transfer is enhanced when either of Ra, Da and $\phi$ is raised. The permeability increment achieved a 12.73% enhancement in the heat transfer rate. Also, when Ha is altered from 0 to 100, a reduction in values of the Nusselt number is given up to 22.22%. Furthermore, the optimal inclination angle for the convective process is $\alpha = 45°$.

## List of symbols

| | |
|---|---|
| Cp | Heat capacitance (J kg $^{-1}$ °C $^{-1}$) |
| $B$ | Magnetic induction |
| Da | Darcy number |
| $K$ | Permeability ($m^2$) |
| $k$ | Thermal conductivity (W $m^{-1}$ $K^{-1}$) |
| $k_{eff}$ | Effective thermal conductivity (W $m^{-1}$ $K^{-1}$) |
| Nu | Nusselt number |
| $P$ | Dimensionless pressure |

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