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Investigation on Natural Convection in a Square Porous Cavity with an Open Side

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ABSTRACT

Natural convection in a porous, rectangular hollow full of saturated air was investigated numerically in the current study. The bottom side was warmed with a continuous heat flux, the right side's temperature was kept at (Tc), the left wall was opened to the surroundings, and the top side was insulated. The pertinent filled-out research parameters in the current experiment were four heat flux values (1500, 3000, 4500, and 6000 W/m^2) and three Darcy's numbers ($Da_1=4.025\times10^{-10}$, $Da_2=4.025\times10^{-8}$, $Da_3=4.025\times10^{-6}$). COMSOL Multiphysics 5.5a, using finite elements and a relying Brinkman-Darcy extended model, was employed to resolve government equations. Local thermal balance simulation was assumed in this solution. Energy transfer and momentum were studied using isotherms and streamlines. The findings appeared that the flow velocity improved with the rising Darcy number, especially in the case of Da3, as well as increasing the average Nusselt number about 110 % and 45% for Da3 and Da2 compared with Da_1. Additionally, the increase in heat flux will increase the heat transfer, especially with Da_3.

Keywords: Natural convection, Porous media, Cavity, Open boundary.

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التحقيق في الحمل الحراري الطبيعي في تجويف مسامي مربع مع جانب مفتوح

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الخلاصة

تم فحص الحمل الحراري الطبيعي في مجوف مربع مسامي مشبع بالهواء درس عدديًا في الدراسة الحالية. الجانب السفلي مسخن بفيض حراري ثايت، الجدار العلوي معزول، الجانب الأيمن مستقر عند درجة حرارة ثابتة بينما الجانب الأيسر مفتوح للمحيط الخارجي. تم تسخين الجانب السفلي بتدفق حراري مستمر وتم الاحتفاظ بالجانب الأيمن عند درجة حرارة ثابتة (Tc) والجانب الأيسر تم فتحه إلى المحيط بينما تم عزل الجدار العلوي. كانت معاملات البحث المكتملة ذات الصلة في التجربة الحالية أربع قيم تدفق حراري (1500 ، 3000 ، 4500 و 6000 واط / متر مربع) وثلاثة أرقام دارسي ($Da_1 = 4\times10^{-10}$, $Da_2 = 4\times10^{-8}$, $Da_3 = 4\times10^{-6}$) . استخدم COMSOL Multiphysics 5.5a ، والذي يستخدم طريقة العناصر المحدودة ونموذج Brinkman-Darcy الموسع المعتمد، لحل المعادلات الحاكمة. تم افتراض نموذج التوازن الحراري المحلي في هذا الحل. تمت دراسة نقل الطاقة والزخم باستخدام توزيع درجات الحرارة وخطوط انسيابية الجريان. أظهرت النتائج أن سرعة التدفق تحسنت مع ارتفاع رقم دارسي خاصة في حالة Da_3 وكذلك زيادة متوسط عدد نسلت بحوالي 110٪ و 45% لـ Da_3 و Da_2 مقارنة مع Da_1. بالإضافة إلى ذلك ، فإن الزيادة في تدفق الحرارة ستزيد من انتقال الحرارة خاصة مع Da_3.

الكلمات المفتاحية: الحمل الحراري، وسط مسامي، التجويف، الحدود المفتوحة

1. INTRODUCTION

Because of its significance in several engineering uses, research into convectional heat transfer through porous material is an essential progression and a quickly expanding topic in contemporary research on heat transfer because it's essential in a variety of applications in engineering, such as solar thermal receivers, building ventilation, electronic cooling devise, metals melting process, thermal insulation devise, and oil extraction. The mechanism of fluid motion in natural convection is based on density variation; the heavy portion of fluid away from a heat source will move under buoyancy force to the hot side, while the light portion (largest heat) transfers to compensate for the moving portion; as the process continues, heat energy transfer will increase **(Kaviany, 1995; Aydin and Yang, 2000; Bejan, 2013)**. A solid with pores is a porous medium; typically, this term refers to interconnected pores that permit one or more fluids to pass through the substance. The porous media sources may be man-made (such as catalytic pellets, wicks, and insulations) or "Naturally" created (such as rock, beach sand, sandstone, wood, sponges, and biological tissues) investigating natural convection in a chamber packed completely or in part by porous material that was too filled with a fluid has been an important topic due to its important in engineering and science applications include solar collectors, solar thermal receivers, insulated strips, and with heat exchangers with expanded surfaces **(Sezai and Mohamad, 1999)**.

Many researches on free convection in the cavities have presented with closed cavities **(Kumar, 2000; Misirlioglu et al., 2005)** studied cavities with natural convection with two vertical wavy walls, the research of (**Kumar, 2000)** shows that mild sinusoidal aberrations from the softness of upward side at a 60 ˚ slope of phase and high-frequency increase convection that is unrestricted from a wall with constant heat flow. The findings of (**Misirlioglu et al., 2005)** are contrasted with those for a square hollow with straight walls discussed in the open literature. Natural non-Darcy convection entire a square cavity holding porous material was studied by **(Nawaf and Pop, 2005).** It was cooled to a consistent temperature on the perpendicular fence T_c, but the cavity's left upward wall grew hot to a steady temperature T_h , horizontal walls behaved adiabatically. The non-dimensional equations that governed the problem were quantitively resolved using the finite volume approach. It was discovered that raising the parameter for inertial effects causes the cavity's natural convection currents to slow down and lowers the typical Nusselt value for constant Rayleigh number values. **(Basak et al., 2006; Sathiyamoorthy et al., 2007)** investigated the square's convection naturally in cavities occupied with porous mediums with the bottom heated wall top insulated wall, but the side upward walls were warmed in (**Sathiyamoorthy et al., 2007)** while cooled in (**Basak et al., 2006)**. **(Oztop and Abu-Nada, 2008)** looked at convection naturally in a rectangle partly warmed enclosure filled with nanoparticles, the vertical left wall is where the flush mounted heater is. While the remaining walls were isolated, the temperature of the right perpendicular surface was less than the heat sources. Rayleigh number ($10^3 \leq$ Ra $\leq 10^5$), heater height (0.1≤ h≤ 0.75), heater position ($0.25 \leq y_p \leq$ 0.75), ratio of aspects (0.5≤ A ≤2), and nanoparticle volume percentage ($0 \leq \varphi \leq 0.2$) were all calculated.

It was discovered that by employing nanofluids, the heat transfer increase is highly noticeable compared to minimal aspect ratios to large aspect ratios. **(Chen et al., 2009)** investigated a wall's top and bottom of a hollow with permeable layers, and the natural convection inside it. The findings include flow patterns and isotherms, local and typical Nusselt numbers over the chilly side for porosity values from 0.2 to 0.8, various Darcy numbers from 10^{-1} to 10^{-6}, Rayleigh numbers from 10^3 to 10^7, and the proportion of container height to the porous layer's thickness from 0 to 0.50, the interface between porous and fluid media was studied using the jump in tension condition, incorporating both inertial and viscous effects. The degree of convection in porous or fluid-filled regions may be described by a Darcy-Rayleigh number with modifications is a novel development. Global heat transfer remains unaltered when its value is smaller than one unit. The Darcy number, Rayleigh number, and the size of the porous layer affect the heat transfer in the recirculation zones, while the porosity value only impacts when Da is high. **(Revnic et al., 2009; Hussein, 2010)** studied the natural convection in inclined cavities. The first study assumed that the cavity has two adiabatic walls, with one wall being heated and another being cooled from within. By means of a core finite-difference technique and Richardson analysis, the governing dimensionless partial differential equations for the average and local Nusselt numbers, the stream function, and isotherms have been numerically solved. The Rayleigh number and the slope of the hollow are found to have a considerable impact on the isotherms, streamlines, and average Nusselt numbers, Rayleigh numbers up to 100 might yield results for tilt angles, while Rayleigh numbers more than 1000 could not yield results for all angles of inclination. In the second study, the walls to the sides were kept at identically high and low temperatures, while those on the top and bottom were thermally insulated. It was discovered that the buoyancy effect causes vortices to form in the two-dimensional flow.

Also, the findings clarify that one cell dominates the flow field, revolving clockwise and filling the hollow. (**Sivasankaran et al., 2010)** worked on natural convection within a permeable square container with separate heating.
The partition's right side experiences isothermal cooling at a decreased temperature, whereas the left contains two distinct heat sources. The left wall's unheated areas, as are the wall's top and lower parts, are adiabatic. The findings show that when the Darcy number and the amended Rayleigh number rise, heat transfer velocity grows, but it decreases as the aspect ratio rises. In practically all parameter scenarios, with the exception of ε=0.5, it is discovered that the typical heat transfer velocity is larger at the heater at the base compared to the upper heater. Additionally, the greatest temperature is often found at the top heater, with the exception of the scenario where ε=0.5, wherever the highest temperature is located on the heater at the base. The findings also showed that the highest temperature increases as the aspect ratio does and lowers with a modified Rayleigh number. Convection, a porous media, discrete heating, the creation of heat, and the finite difference technique.
In a computational analysis of layers of porous fluid that are locally heated from below, two-dimensional natural convection was examined by **(Bagchi and Kulacki, 2011)** Rayleigh number based on domain aspect ratio, Darcy number, length of the heater to the hollow, the ratio of porous layer to hollow elevation, and total layer height were five dimensionless factors whose impacts on the total Nusselt number are examined. Convective movement is limited by porous area with a few exposures through the fluid layer that lies on top according to streamline and isotherm patterns. The Nusselt number rises when the heater's height-to-length proportion falls, and the Darcy number rises. Impacts of heat transfer coefficient in relation to height proportion and Darcy number were not impacted by how big the heat source is. Complex flow reorganization is seen in domains with large aspect ratios along a rise in the Rayleigh number. **(Kalaoka and Witayangkurn, 2012)** studied a square, porous container with a vertical wall that is only partly cooled and experiences natural convection. The cavity's right-side wall is partly chilled while the cavity's left-side wall is heated. The cooled area is close to the top wall, and the walls still present are adiabatic. It is discovered that when Darcy number and Grashof number rise, fluid motion strength, streamline magnitudes, and temperature distribution all change. Additionally, the enclosure forms one circulation cell that rotates in a clockwise orientation. Higher Darcy numbers result in bigger heat line magnitudes, but increasing Grashof's number does not impact heat line magnitudes. A rectangle area using a medium with pores and a left vertical wall is heated sinusoidally, and a visual representation of natural convection heat transfer is analyzed **(Khansila and Witayangkurn, 2012)**. The enclosure's lower portion is heated, and its top portion is chilled. The issue was examined for various magnitudes of the Rayleigh number $10^3 \leq Ra \leq 10^6$, aspect ratio ($0.5 \leq AR \leq 2$), and Darcy number $10^{-1} \leq Da \leq 10^{-3}$, it is maintained that the Prandtl number (Pr) is 0.71. Heat lines, isotherms, and streamlines display the findings; two circulations exist inside the container for the streamlines. With rising Rayleigh and Darcy numbers, the values of streamlines and heat lines rise. **(Thorpe, 2015)** examined a comparison of several models for a constrained fluid's inherent convection over a porous layer. Among the vertical walls, one was warmed, and the other was cooling, but the upper and lower sides were insolated. When the Darcy model is employed, the beavers-Joseph Imperial boundary circumstance at the fluid/porous stratum contact is triggered. It was discovered that, for Darcy, values up to around 10^{-4}, all three models produce results that are very comparable when governing equations have been resolved using the ADI technique. The extended Darcy model by Brinkman and Forchheimer is favored at larger Darcy numbers because it absorbs the impacts of inertia into consideration. A numerical study was

done on the heat transfer by coupled natural convection in a partly heated porous container **(Ammar et al., 2018)**. The limited wall depth (0.02 ≤ D ≤ 0.5), the thermal conductivity coefficient (0.1 ≤K_r ≤10), alternative Rayleigh number (10 ≤Ra ≤10^3), and the ratio of aspect (0.5 ≤ A ≤10) have all been taken into consideration when using the classic Darcy model. The findings suggest that heat transport may be improved by raising the thermal conductivity ratio and modifying the Rayleigh number. Wall thickness's implications on the process of heat transfer are being examined, and it has been discovered that as the size of the wall's thickness rises, the transfer of heat through conduction will predominate. Additionally, raising the aspect ratio will improve stream performance and slow heat transmission. Computational modeling in a porous container with natural convection in a lower wall-mounted heater was analyzed **(Huq et al., 2019)**. The top side of the hollow was cooled, and the vertical surfaces were maintained at adiabatic to adjust the cavity's heat transfer. A heater is put at various points on the cavity's lower side. The Boussinesq approximation and the Brinkman extended Darcy flow mode are used to build governing equations to characterize the heat transfer rate and the heat flow routes. The finite element technique is applied with the given boundary conditions to resolve dimensions-free governing equations. The Darcy number (Da), Rayleigh number (Ra), Prandlt number (Pr), the ratio of porous media's thermal conductivity (k), length and placement of the heater were the variables that determined the solution to the issue. Three alternative heater sites at the lower walls with varying heater lengths and varied values of Ra changing between 104 to 106 were considered to evaluate the impacts of different heater lengths and positions on cavity natural convection. For the aforementioned parameters, simulation outcomes were reported regarding streamlines, isotherms, and the average Nusselt number at the heated side inside the void. The findings reveal that the speed at which the heated wall is transferring heat, the realms of flow and heat, are profoundly affected by the heater's length, positions, and Rayleigh number. Flexible fin's effects on convection naturally in a somewhat permeable hollow were researched by **(Saleh et al., 2020)**. The fin is placed on the warmed left side of the container. The governing equations were spoken in the structural and fluid realms using the Arbitrary Lagrangian-Eulerian (ALE) formulation, then resolved by FEMure. The outcome demonstrates that the fluctuating fin affects the region under the fin instead of the region up the fin or the region in the middle. As the fin elasticity rises, the thickness of the fluid layer, the Darcy number, and the heat transfer velocity are enhanced. As the oscillation amplitude increases, the overall velocity of heat transfer rises tremendously. The heat transfer velocity might increase by 3.4 percent with an oscillation amplitude of 0.1. **(Zachi and Ali, 2021)** analyzed the natural convection of heat in a chamber partly filled with a porous substance warmed with a continuous heat flux. The theoretical examination of the feats of heat transfer was carried out due to the impacts of continual heat flow bottom heating (q=150,300,450,600W/m^2) for three heaters of sizes (0.2,0.14,0.07)m, two vertical walls cooling evenly at a fixed temperature, and the upper wall was adiabatic, four distinct porous medium levels
(Hp=0.25L,0.5L, 0.75L, L), Rayleigh number range (60.354 - 241.41), Darcey number (Da_1) 3.025× 10^{-8} and (Da_2) 8.852× 10^{-4}), and (1.304× 10^6 - 5.216× 10^6) for Da_1 and Da_2 instances correspondingly are the key filled researched parameters. For the area of porous media, the regulating equations with dependent Brinkman-Darcy expanded mode were computed using COMSOL Multiphysics 5.5a®, which is dependent on the Galerkin finite element method. The findings demonstrate that, in addition to the rising level of the typical Nusselt number, raising the Rayleigh number impacts the temperature profile. The local Nu distribution is symmetrical throughout the warmed bottom side and is lowest at the lower

midway. Additionally, the greatest heat transmission and fluid flow are obtained at 0.25L of porous layer thickness, evident with high heater sizes and around (93%) for the average Nu. An analysis of employing mathematics to simulate natural convection in an oblong container with a porous medium's horizontal layers was examined by **(Asmaa and Luma, 2022)**. The cold lateral walls, insulated top wall, and bottom heated wall with consistent heat flow were used to establish the system limits. The heater length ($7\leq \zeta \leq 20$ cm), porous medium thickness ($5 \leq H \leq 20$ cm), and continuous heat flux ($150 \leq q'' \leq 600$ W m^2) were chosen as the three parameters for the investigation. The foam made of copper metal had a porosity of 0.9 and a PPI (pore density) of 10, and it was drenched in a fluid having a Prandtl number of 0.7. The speed of heat transfer was found to be (51.4%) at a 5 cm porous thickness of the layer greater than at a layer height of 20 cm (i.e., when the void is filled). At equivalent in thickness, the speed of heat transfer was also revealed to be (74.6%) higher than at a half-filling (H = 10 cm). Additionally, utilizing the heater's greatest dimensions and the thinnest porous layer depth maximizes the local and mean Nusselt number. Finally, improved circulation and convective modes were seen at high heat flux levels.

(Hussain and Ali, 2023) studied organic convection, a plane wall's heating of a thermal stratification environment. The method of finite differences combined with the Alternating Direct Implicit Scheme is used to compute the government equations of continuity, momentum, and energy computationally. For different values of physical parameters, the Nusselt number, temperature distributions, and velocity were studied quantitatively and displayed through graphs. The ANSYS software was also utilized to find a solution. The findings demonstrate that the influence of the differentiation factor is minimized with growth in the Prandtl number and that an increase in the Grashof number does not change the influence of the stratification factor. In earlier investigations, viscous fluid-filled cavities with partial or complete openings were investigated **(Miyamoto et al., 1989; Khanafer and Vafai, 2002; Kiwan and Khodier, 2008; Al-Hassan and Ismael, 2019)**. An analysis of a flow caused by buoyancy resulting from a source of heat of limited size fixed on the straight wall of an enclosure with a one-side entrance in a partially opened enclosure is done numerically by **(Abib and Jaluria, 1988)**. They found that as the Rayleigh number rises, convection takes over as the primary transportation mechanism. Also, they discovered that the resonance zone shrinks and travels toward the vertical wall as the Rayleigh number rises. **(Bilgen and Oztop, 2005)** computationally analyzed transferring heat via natural convection in rectangle chambers with a slope. Aperture size without dimensions which varies from 0.25 to 0.75, the site of the aperture at the top, middle, and lower points, and the angle within the opening, which ranges from 0 (looking up) to 120 (looking down 30 degrees) are all factors in the parametric research. The Rayleigh number, which runs from 10^3 to 10^6, is also a factor. They found that the aperture size, Rayleigh number, and typical aperture placement were rising functions of the Nusselt number and volume flow speed. Utilizing the lattice Boltzmann technique investigated the possibility of simulating convection naturally in a rectangle with ends open chamber complete with a porous material **(Haghshenas et al., 2010).** The thermal model has been expanded utilizing the lattice Boltzmann technique and the Taylor series expansion based on the least-squares equation, and the hydrodynamic and heating fields are simulated using the double-population approach. By including the porosity in a balanced distribution coefficient and the force term in the development equation, the impact of a porous material is considered. Dynamic fluids and heat transfer in the non-Darcy regime are predicted using the Brinkman-Forchheimer formula, which incorporates the viscous and inertial factors. A thorough parametric analysis of flows of convection that occur naturally was conducted for the Rayleigh number range and porosity values. It has been discovered that these two factors notably affect heat transfer.

(Oztop et al., 2011) investigated utilizing the Brinkman-Forchheimer technique to explain natural convection in a partly opened container occupied with a porous medium. The other sides of the hollow were thermally or adiabatically insulated if the cavity's left vertical wall was heated. The impacts of important factors such as the Grashof, Darcy numbers and porosity, the distance along the warmed wall, and the placement middle of the opening enclosure were investigated based on numerical predictions. They observed that when the Grashof number rises, the local Nusselt number rises when a perpendicular wall is partly heated, owing to stronger buoyancy-driven flows at a specific spot on this wall. The outcome was, the heated wall's temperature raised.

Square-shaped natural convection porous container utilizing the spectral collocation approach with local equilibrium of temperature and non-equilibrium models had examined by **(Chen et al., 2016)**. The Chebyshev polynomials were utilized to estimate the temperature and stream function, and the Chebyshev-Gauss-Lobatto collocation points were utilized to discretize the governing equations without dimensions. The discretized equations are solved using the two-step approach, the matrix diagonalization method. The findings demonstrated that to assess the precision of the technique, accurate remedies for the model of local thermal equilibrium has been developed, and it was found throughout the investigation that the Chebyshev spectral collocation formula can give results with a high degree of accuracy. In addition, the Rayleigh number, the thermal conductivity ratio, and the inter-phase temperature-transfer efficiency were used to assess the isotherms and streamlines to show the heat transfer and fluid flow for different factors. **(Chen et al., 2018)** examined three benchmark tests to support the LB model in a square hollow that is open on one end and partially packed. They used the LB approach to explore how the permeability, liquid-to-porous temperature ratio of conductivity, and thickness of the porous layer affect thermal convection naturally coupled. They discovered that each of these variables considerably affects the paths of the thermal and stream regions.

Computer research on a hollow with a cover and porous medium that experiences mixed convection that is partly heated and has an open side was analyzed by **(Nidal et al., 2020)**. On the lower wall of the hollow, a heater is flush placed for varied parameters such as Richardson number (0.1, 1, 10), heater length (1/5, 2/5, 4/5), and Darcy number (0.1, 0.01, 0.001). The equations that governed were resolved by developing a computer program employing the confined volume method. Due to the sliding lid, side wall that is not closed, and heater, observations reveal that the hollow's internal fluid movement and heat transfer pattern is quite complicated. Heat transfer increases as Grashof numbers and heater length grow but decreases with Darcy numbers.

The numerical investigation of a three-dimensional cavity in a hollow containing a porous medium made from a saturated fluid has been examined by **(Mohammed and Ali, 2021)**. Two discretized heaters were used to maintain two insulated bottom walls; vertical walls on the right and left are kept at identical temperatures in different places. The thermal characteristics, including average Nusselt numbers and interface wall temperature, were determined. These parameters included the placement of two heaters with fixed top-to-bottom distances (S) and distances (s) between them at a fixed Rayleigh number (Ra) of 6.15 $\times 10^6$ and fixed porosity magnitudes (0.418). The findings indicated that the position of the heaters might somewhat improve natural convection. The variation in local Nu number was readily visible throughout the heaters' length and width. The local Nu was the largest in the hollow's halfway length.

Finally, it can be seen from the literature that has been given that writers completed their work for various case studies using square cavities that were opened or partially opened and filled with porous material. However, little focus has been placed on researching how bottom heating, in addition to openings and porous material, affects heat transmission mechanisms thus, the primary goal of the present research is to quantitatively quantify natural convection in a chamber containing porous material that is opened on the left side while being thermally constant on the right with (Tc=35ºC), the bottom side is warmed by a continuous heat flux, and insulated on the top wall as shown in **Fig. 1**. The container was occupied with glass beads as porous media which is made of soda lime glass with diameter (2.4mm-2.9mm). Several controlling elements were investigated in the provided case study to ascertain how they influenced heat and fluid flow.

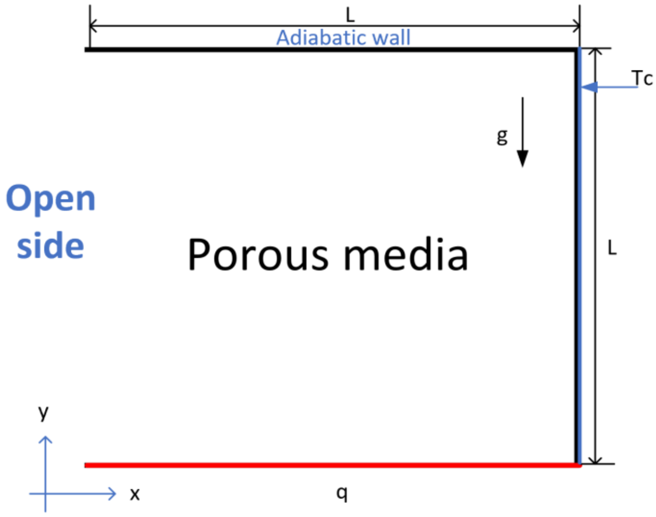


Figure 1. The problem's actual physical geometry.

2. NUMERICAL SIMULATION

The present study's assumptions ensure the enclosure's internal flow is steady and laminar. Local thermal balance exists everywhere amid the convective fluid and the solid. Inside the cage, the operating fluid is air because of the open side, which has uncrossable boundaries and a lack of internal heat production. Viscous dissipation, radiation heat transfer, thermal scattering, pressure force, and chemical reaction are inconsequential. **Table 1.** lists the necessary parameters for the porous media (glass beads) employed in this study. The constant two-dimensional, Cartesian coordinates and free convection governing equations were regulated by the fundamental physics of mass, momentum, and energy conservation (Darcy model with Forchheimer-Brinkman extensions). As a result, the governing equations are formulated and represented in dimensional form. As:

2.1 The equation for mass conservation (continuity)

$$\frac{\partial u_p}{\partial x} + \frac{\partial v_p}{\partial y} = 0 \quad (1)$$

2.2 Momentum equation

$$\frac{1}{\varepsilon^2}\left[u_p \frac{\partial u_p}{\partial x} + v_p \frac{\partial u_p}{\partial y}\right] = -\frac{1}{\rho_{air}}\frac{\partial p}{\partial x} + \frac{\mu_{air}}{\varepsilon \rho_{air}}\left(\frac{\partial^2 u_p}{\partial x^2} + \frac{\partial^2 u_p}{\partial y^2}\right) - \frac{\mu_{air} u_p}{\rho_{air} K_p} \quad (2)$$

$$\frac{1}{\varepsilon^2}\left[u_p\frac{\partial v_p}{\partial x}+v_p\frac{\partial v_p}{\partial y}\right]=-\frac{1}{\rho_{air}}\frac{\partial p}{\partial y}+\frac{\mu_{air}}{\varepsilon\rho_{air}}\left(\frac{\partial^2 v_p}{\partial x^2}+\frac{\partial^2 v_p}{\partial y^2}\right)-\frac{\mu_{air}v_p}{\rho_{air}K_p}+\beta_{air}g(T-T_o) \quad (3)$$

where:

- ε is the porous media's porosity
- u_p, v_p are the velocity components of porous media
- ρ_{air}, β_{air} are the density and thermal expansion coefficient of air, respectively
- k_p is porous media thermal efficiency
- μ_{air} is the fluid's dynamic viscosity

2.3 Energy equation

$$u_p\frac{\partial T}{\partial x}+v_p\frac{\partial T}{\partial y}=\alpha_{eff}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (4)$$

Effective thermal diffusivity is defined by:

$$\alpha_{eff}=\frac{k_{eff}}{(\rho c_p)_{air}} \quad (5)$$

Where the effective conductivity ($keff.$):

$$k_{eff}=\varepsilon k_f+(1-\varepsilon)k_s \quad (6)$$

(kf, ks): fluid and solid conductivity, respectively.

Table 1. The characteristics of porous medium.

The Parameters	Values
Diameter	2.4−2.9 (mm)
Porosity (ε)	0.418
Permeability (K)	1.61*10^{-9} (m^2)
Density (ρ)	2515.91 (kg/m^2)
Thermal conductivity (k)	1.072054 (W/m.K)
Specific Capacity (Cp)	1329 (J/Kg.K)

2.4. Boundary Conditions

Top side wall:

u=0, v=0 and $\frac{\partial T}{\partial y}=0$ at y=L, 0 ≤ x ≤ L

Right side wall:

u=0, v=0 and T=Tc at x=L, 0 ≤ y ≤ L

Left side wall:

$\frac{\partial U}{\partial X} = -\frac{\partial V}{\partial Y}, \frac{\partial T}{\partial x} = 0$ at x=0, 0 ≤ y≤ L

where: T_o=ambient temperature

bottom side wall:

q= h(ΔT), u=o, v=0 at y=0, 0 ≤ x ≤ L

$qconduction = qconvection = -kf\frac{\partial T}{\partial y} = h\ (T - T_o), u = 0, v = 0$

The average Nusselt ($Nu_{avg.}$) and local Nusselt (Nu_x) are employed as illustrated below along the cavity's side towards the heat flux:

$$Nu_x = \frac{\text{heat transfer by convection}}{\text{heat transfer by conduction}} = \frac{q*L}{k_f(T-T_c)} \quad (7)$$

$$Nu_{avg.} = \frac{1}{L}\int_0^L Nu\,dx \quad (8)$$

Table 2. Thermophysical characteristics of air and glass beads.

Properties	Air	Glass Beads
ρ (kg/m^3)	0.99	2510.52
c_p (J/kg.K)	1006	670
k (W/m.K)	0.03	0.87

3. NUMERICAL TECHNIQUE

The Commercial Software, COMSOL Multiphasic 5.5, has been depended on to analyzed and display the hollow containing a fluid-moving, porous material for distributing temperature and natural convection. Based on FEM, heat transfer equations and the flow field are solved. One of the key benefits of using the finite element method is that it offers a high level of versatility according to the components that may utilized to separate spaces as well as the foundation works. An optimal mesh for the computational domain is necessary for computational fluid dynamics solutions. To achieve high accuracy, a lot of cells are required. To create the computational domain in 2D Cartesian coordinates, (1296) triangular mesh elements are used, as shown in **Fig. 2.**

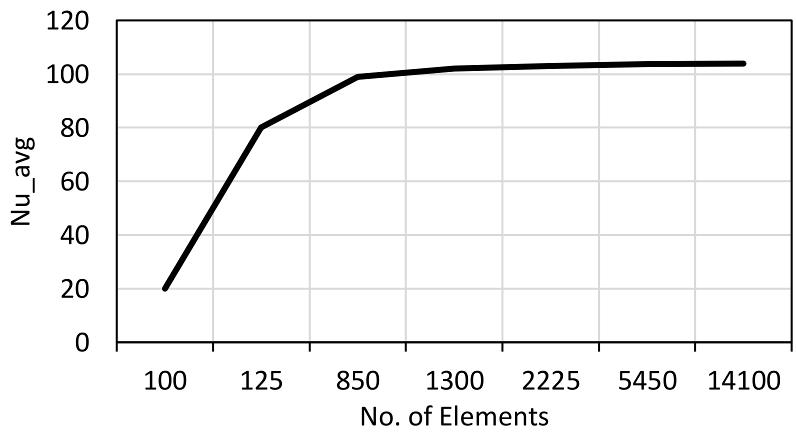
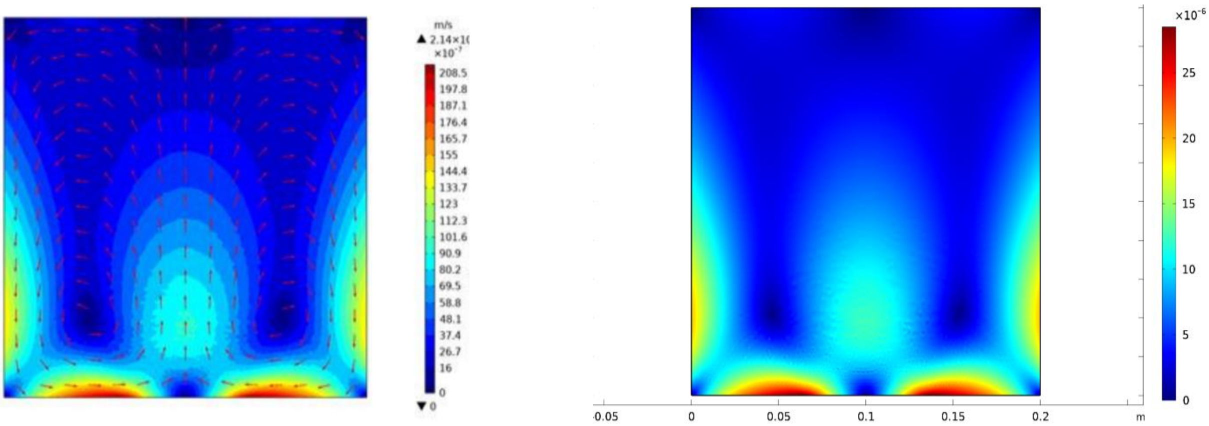


Figure 2. Average Nu with No. of Elements at q = 4500 W/m^2, Da = 4 x 10^{-8}

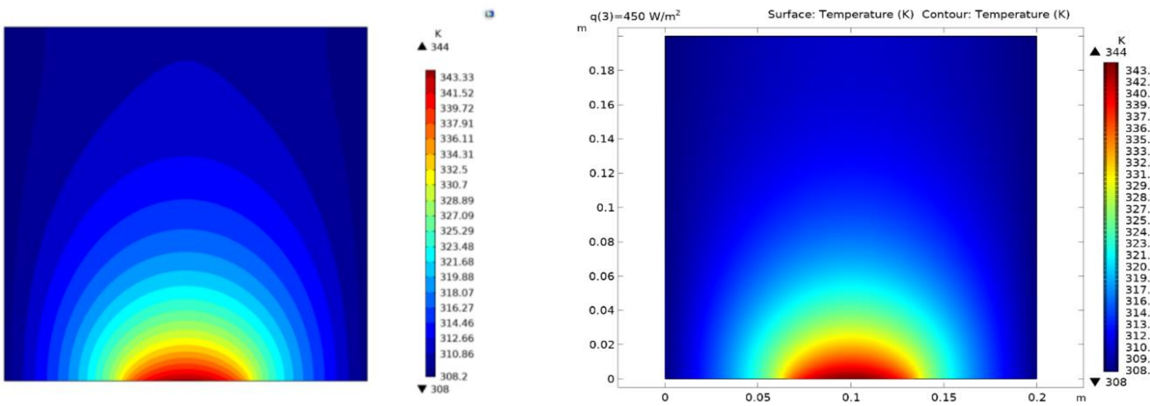
4. RESULTS AND DISCUSSION

An open cavity containing fluid-saturated porous media is used to study natural convection behavior with variations of heat flux and Da. One lateral side is open and the other is preserved at a consistent temperature (Tc = 35°C). The physical properties of glass beads and air are depicted in **Table 2.** Various heat fluxes are taken into consideration (q=1500, 3000, 4500, and 6000 W/m^2), Darcy number ($Da_1 = 4 \times 10^{-10}$) ($Da_2 = 4 \times 10^{-8}$), ($Da_3 = 4 \times 10^{-6}$), with porosity (0.418) and permeability (1.61×10^{-11}, 1.61×10^{-9}, 1.61×10^{-7}) m^2, for Da_1, Da_2 and Da_3, respectively. Predefined data have been compared with published research in several instances and models for streamlines and isotherms. The current research is compared with **(Zachi and Ali, 2021)** to ensure that the softwarproperly analyzes and examines the present task, as shown in **Figs. 3 to 5**.



(a) (b)

Figure 3. Streamlines (a) previous study **(Zachi and Ali, 2021)** and (b) present work.

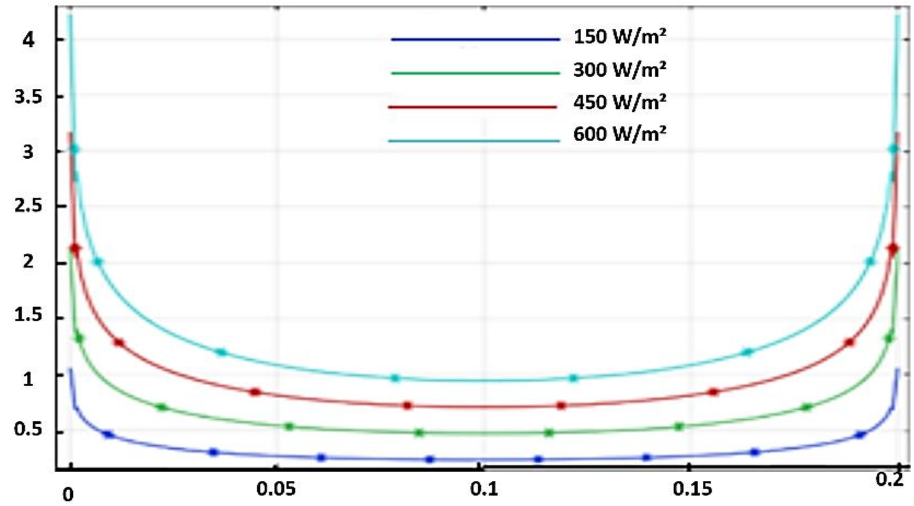


(a) (b)

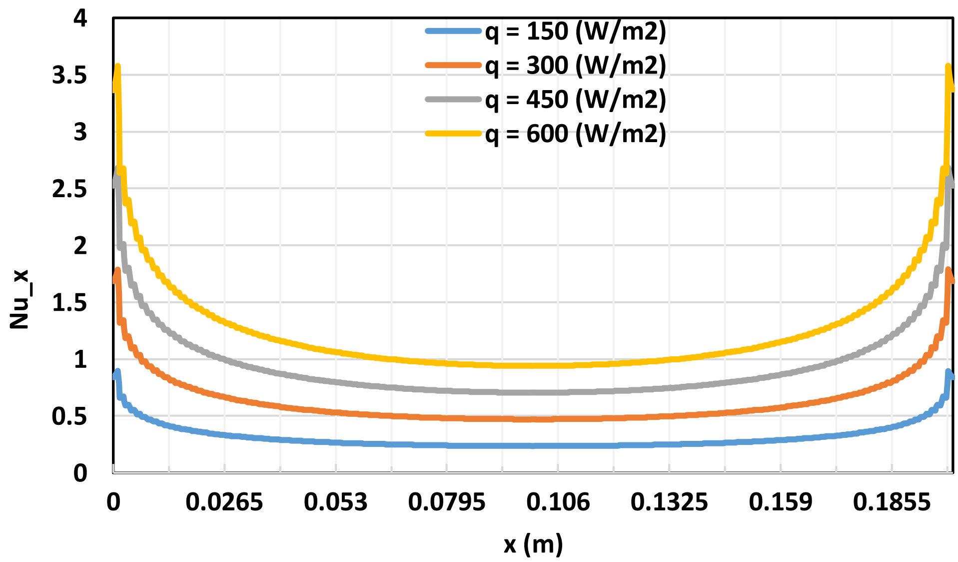
Figure 4. Isothermal contour (a)previous study **(Zachi and Ali, 2021)** and (b) present work.

The comparison indicates that the flow structure, temperature gradient, and Nu number exhibit the same behavior with a deviation of about 10%.

Fig. 6 shows heat flux's impact on natural convection by streamlines of the velocity field for Da_1, Da_2, and Da_3. The results indicate that the flow pattern is the same for all three types and all magnitudes of heat fluxes. It takes two semi-circular-shaped cells, completed one cell in a clockwise direction near the right cold side and the other uncomplete cell in an anticlockwise direction. The right cell concentrates more with Da increase, and the left cell expands more. The inlet velocity gives higher values at the left lower and upper corners. It is noted that the air streamline intensity increases with Da decrease and heat flux increase. This means an increased bouncy effect due to heat flux, and porous media penetrates the air more. Also, the effect of heat flux will be clear at Da_3 because the porous media restriction decreases with Da increase. So, the maximum velocity is at q=6000 w/m^2 for all cases, and the inlet velocity at the left bottom is high for the case of (Da_3) for all magnitudes of heat fluxes because of its higher permeability, which allows for more flow to enter the cavity relative to other Darcie's values (Da_1 and Da_2).



(a)



(b)

Figure 5. Local Nu number with different heat flux (a) previous study **(Zachi and Ali, 2021)** (b) present work.

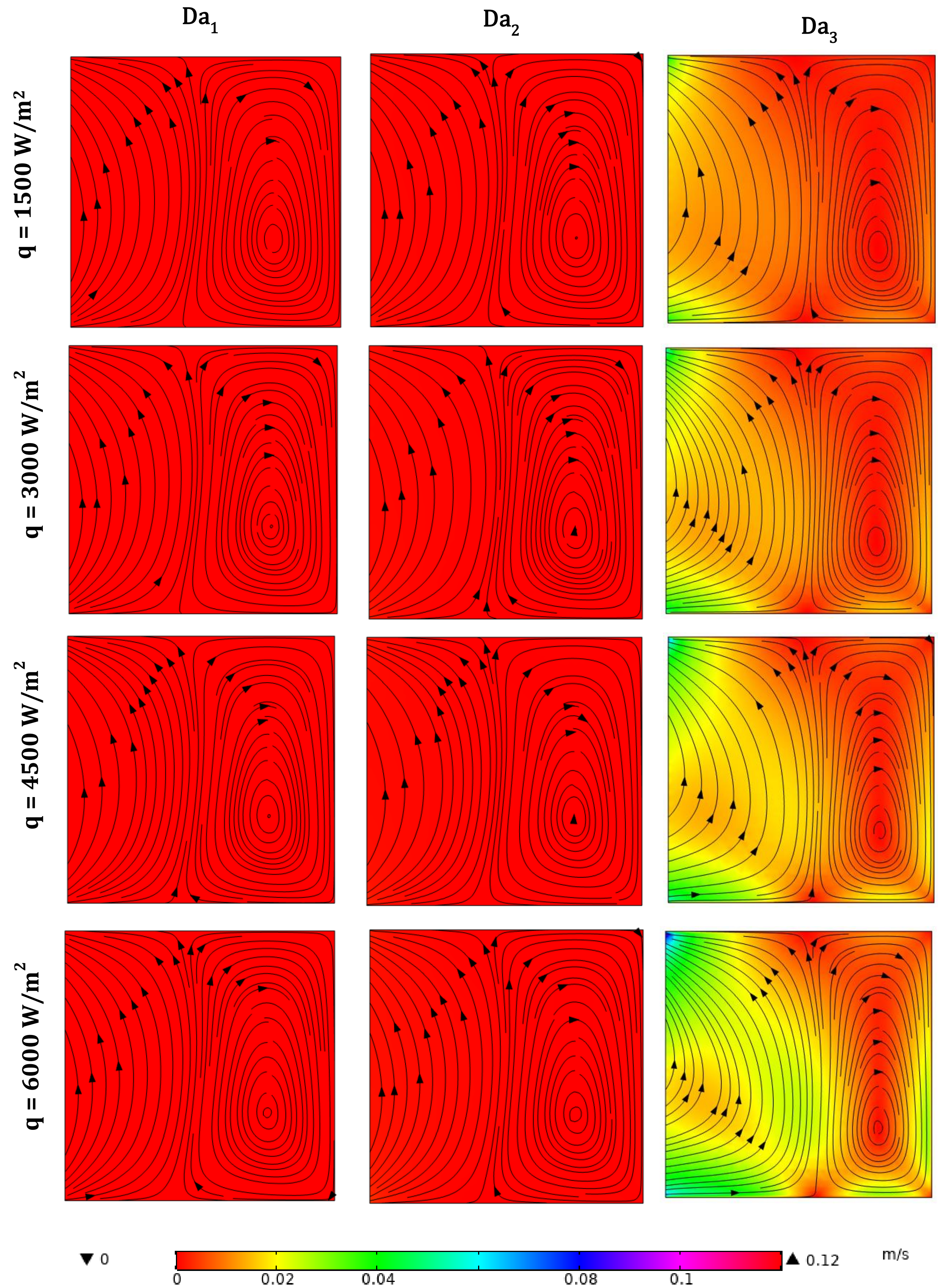


Figure 6. Heat flux's impact on streamlines at various Darcy number values.

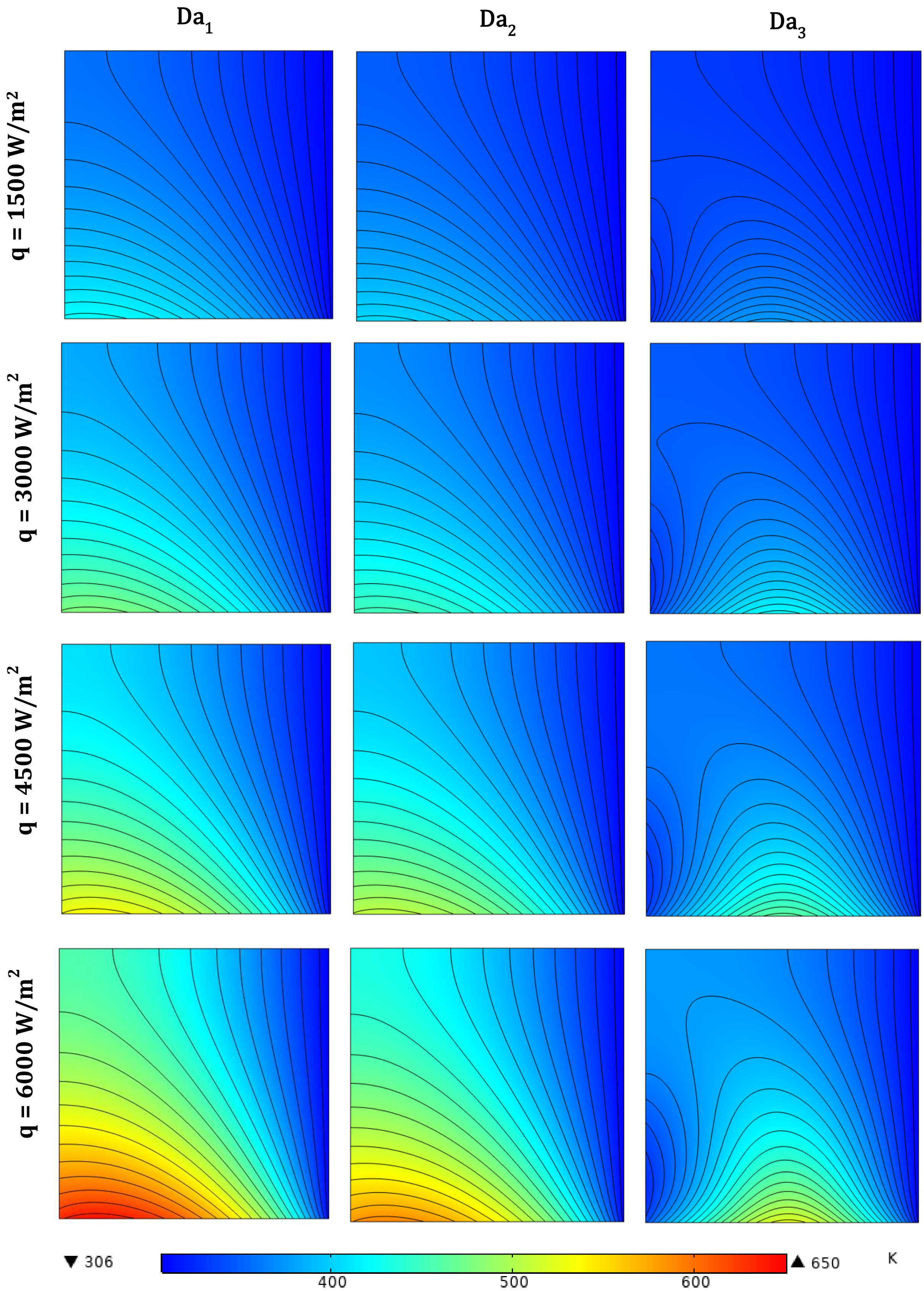
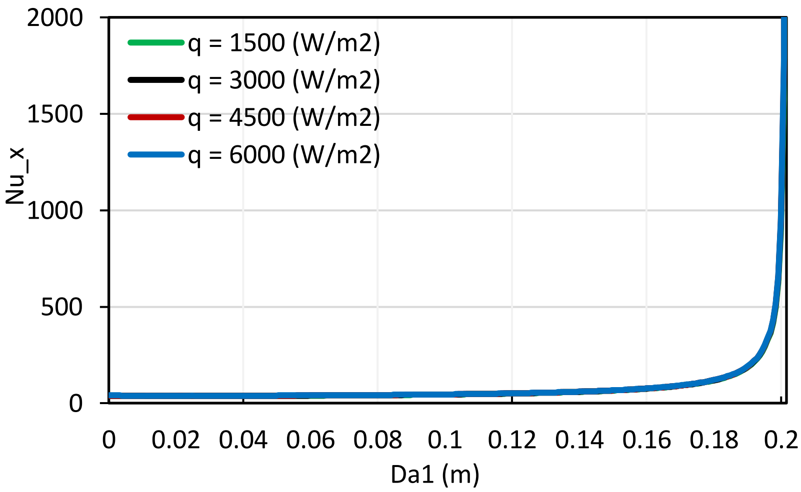


Figure 7. Heat flux's impact on isothermal lines at various Darcy number values.

The isothermal lines are shown in **Fig. 7**. Due to the heater and the obstruction of the porous layer, it is seen that the temperature is high on the left-bottom side for all heat flux values at Da_1 and Da_2, and the temperature decreases toward the right side because of the effect of the cold wall. That means the cold wall with constant temperature is more effective than the open side in the heat transfer process at low Da. This is because of the low penetration of air through the porous media at low permeability. But at Da_3, the temperature distribution is approximately symmetry, which means increasing the influence of the open side on the heat transfer process with an increase in Da. The low temperatures are obtained in the case of Da_3, also due to the higher permeability, which allows for more flow to enter the cavity and decreases its temperature. In the case of Da_1, the heat transfer has improved with a rise in heat flux, especially at (q=6000 W/m^2), among other cases, because of increasing conduction heat transfer through the porous media.

Fig. 8 illustrates the local Nusselt number with cavity length for varying values of heat flux and Da. Furthermore, the right cold wall and left open side affect heat transfer inside the cavity, and the heat flow wall's Nusselt number values are asymmetric. Since the least effective flow velocity is found at the intersection of the asymmetric rotation cells, the heat flux's center is frequently where the lowest local Nu values are found. As a result, conduction dominated heat transfer in this location and the local Nusselt values are the lowest. Among these cases, the maximum values of Nu numbers are obtained in the case of (Da_3) as permeability increased, which increased the flow velocity and convection, so the Nu number increased. **Fig. 7** shows that at Da_1, the lowest Nu is on the open side, while the higher Nu is at the chilly wall. This results from the high restriction for air currents to penetrate the cavity. But with an increase in Da to Da2, the open side will be more effective in heat transfer process, which is clear at Da_3.

Fig. 9 depicts the average Nu for various heat flux values and Da. However, because a more significant portion of the porous medium is exposed to heat flow, the average Nu grows proportionally with heat flux in all circumstances along the heater. With an increase in Da and heat flux, the average Nu rises. The heat flux effect will increase at high Da because the porous media's permeability has increased, which means the convection mode will be the dominant mode.



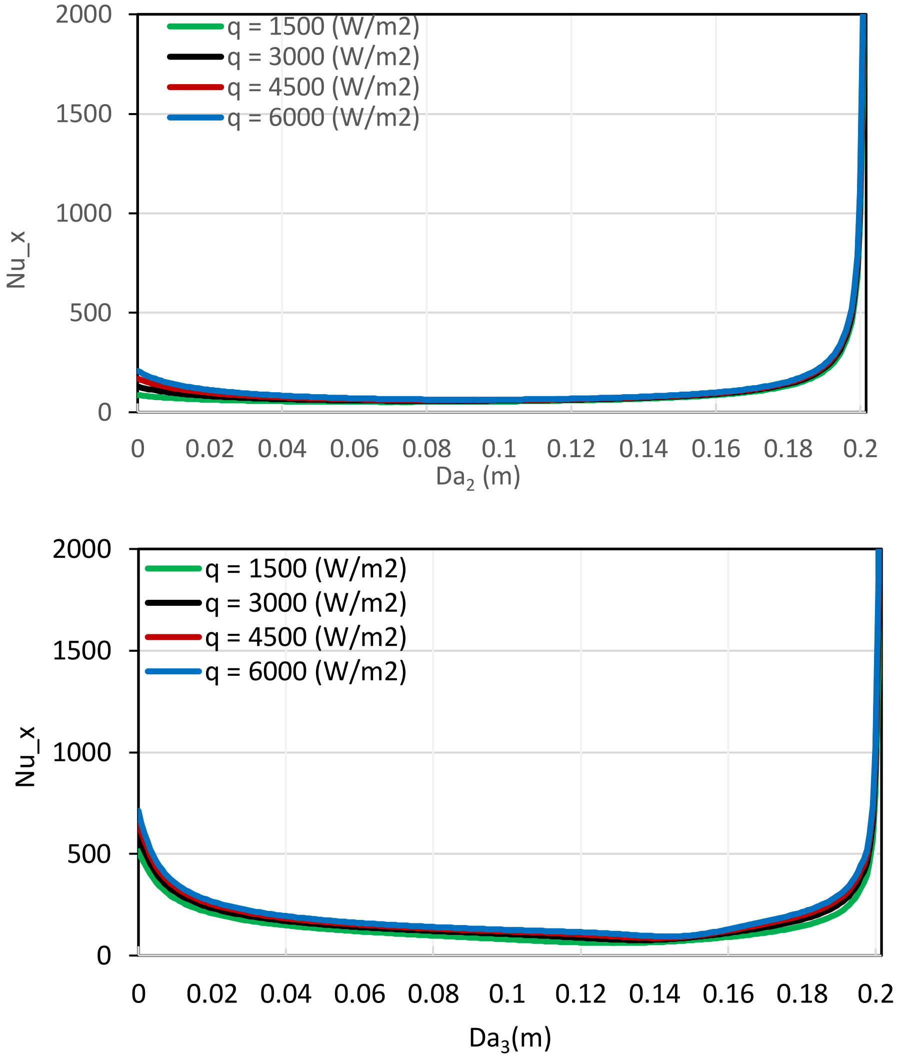


Figure 8. Local Nusselt number changes with cavity length for different heat fluxes and Da.

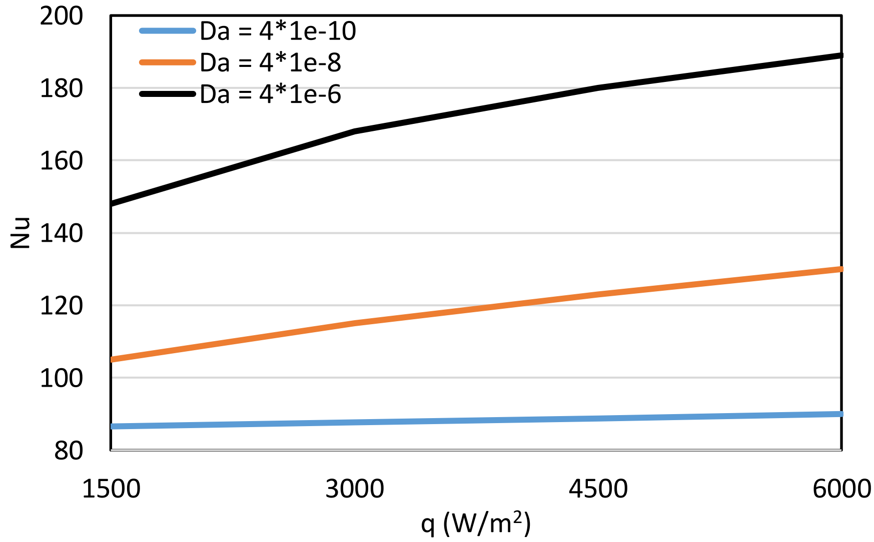


Figure 9. The change in average Nu number with heat flux for various Da values

5. Conclusions

Natural convection and heat transfer in an open enclosure are investigated. The right wall is cold. The top side is insulated, and the lower side is heated. The impact of heat flux and Darcy numbers Da_1, Da_2, and Da_3 are studied with a porosity 0.418. It was concluded that:
1-The free currents velocity for the case of (Da_3) is high due to high permeability.
2- Heat transfer development happened in Da3, especially at (q = 6000 W/m^2), among other cases.
3- Best improvements of heat transfer by increasing Da are 110% and 45% for Da_3 compared with Da_1 and Da_2, respectively, at (q = 6000 W/m^2).

NOMENCLATURE

Symbol	Description	Symbol	Description
A	Open aspect ratio	L	length, m
AR	Aspect ratio	Nu	local Nusselt number
cp_{eff}	Effective specific heat capacity, J/Kg.K	$Nu_{avg.}$	average Nusselt number
cp_f	Fluid's specific heat capacity, J/Kg.K	p	pressure, N/m^2
cp_s	Solid's specific heat capacity, J/Kg.K	q	heat flux, W/m^2
d	Glass beads diameter, m	Ra	Rayleigh number
Da	Darcy number	T	air temperature, °C
H	Open side height, m	x	dimensional length of the x-axis, m
h_x	Heat transfer coefficient, W/m^2.K	ρ_{air}	air density, kg/m^3
K	Porous permeability, m^2	Δ	difference between two values
k_{eff}	Effective thermal conductivity, W/(m.K)	ε	porosity
k_f	Fluid's thermal conductivity, W/(m.K)	μ_f	fluid dynamic viscosity, kg.m/s
k_s	Solid's thermal conductivity, W/(m.K)		

Credit Authorship Contribution Statement

Mazin F. Fateh Ala: Writing – review & editing, Writing – original draft, Experimental work.
Raed G. Saihood: Writing – review & editing, Methodology.

Declaration of Competing Interest

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

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