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Analysis of Transient Behaviour in a Porous Medium-Filled Square Cavity Using COMSOL

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Abstract

This study investigates the transient behaviour of free convection within a square cavity filled with a porous medium, utilizing the COMSOL Multiphysics software. The dimensionless equations for continuity, Darcy, and energy were solved by producing streamlines and isotherms. The analysis was conducted using Rayleigh numbers (*Ra*). The focus lies on examining how Rayleigh numbers influence heat transfer and fluid flow evolution. The findings highlight the transition from conduction-dominated to convection-dominated heat transfer, demonstrating the impact of buoyancy forces in the system. The study solves by simulating a system where one vertical wall is heated, the opposite wall is cooled, and the horizontal walls are insulated. These findings underscore the efficacy of COMSOL in modelling complex thermal phenomena and contribute insights relevant to engineering applications, including cooling systems and thermal energy management.

1. Introduction

Heat transfer, a fundamental process in thermal sciences, takes place through conduction, convection, and radiation. Convection stands out because it involves fluid motion caused by temperature differences, which leads to density variations [1]. Free convection is particularly intriguing because it occurs naturally, driven by buoyancy forces, unlike forced convection, which requires external mechanisms like fans or pumps. This type of heat transfer is common in various engineering and natural systems, such as geothermal energy extraction, building cooling systems, and thermal management technologies [2].

When free convection happens in cavities filled with porous materials, the complexity increases significantly. Porous media have a network of voids and solid matrices that resist fluid movement and influence heat transfer characteristics. Modelling these systems requires solving coupled equations for momentum and energy, making it a challenging yet rewarding field of study [3]. Research has also shown that factors such as Rayleigh numbers, boundary conditions, and the geometry of the cavity play a crucial role in shaping flow patterns and heat transfer efficiency [4]. [3] studied inclined porous cavities and revealed how the angle of inclination and Rayleigh numbers affect flow behaviour, particularly the formation of vortices near cavity edges. Other studies highlighted the influence of buoyancy and magnetic fields on convection heat transfer, demonstrating that while magnetic fields significantly affect liquid metals, their impact on other fluids is relatively minor. Later research expanded on these findings by investigating the effects of additional parameters such as inclination, heat generation, and nanoparticle inclusion [5].

Research on more complex configurations, such as cavities with internal heat sources, has shown that such setups tend to reduce overall heat transfer efficiency due to added thermal resistance (6). Investigations into composite cavities with porous materials have highlighted how Rayleigh numbers and porosity significantly impact temperature distribution and fluid velocity, emphasizing the importance of optimizing cavity properties for better heat dissipation (7).

Thus, this research aims to use COMSOL Multiphysics to explore the transient behaviour of free convection in a square cavity filled with porous media. The focus is on analysing streamlines of free convection, determining the isotherms, and investigating the transient phase. The study on transient free convention, which focuses on how the process evolves over time, have provided valuable insights in examining the progression of streamlines and isothermal in square cavities (8).

Nomenclature

g	Gravitational acceleration
K	Permeability of the porous medium
L	Cavity height/width
Ra	Rayleigh number for porous medium
t	Time
T	Fluid temperature
u, v	Velocity components along x- and y-axes, respectively
U, V	Non-dimensional velocity components along X- and Y-axes,
x, y	Cartesian coordinates
X, Y	Non-dimensional Cartesian coordinates

Greek Symbols

α	Effective thermal diffusivity
β	Coefficient of thermal expansion
υ	Kinematic viscosity
ψ	Stream function
Ψ	Non-dimensional stream function
σ	Ratio of composite material heat capacity to convective fluid heat
τ	Non-dimensional time
θ	Non-dimensional temperature

2. Methodology

The rectangular 2-D square cavity filled with a porous medium used in this work is shown in Fig. 1. The cavity features one heated vertical wall, while the opposite wall is cooled, and the top and bottom walls are insulated. This study evaluates heat transfer and fluid dynamics using Rayleigh numbers (Ra) values to observe the transition from conduction-dominated to convection-dominated heat transfer. The mathematical formulation includes the Darcy and energy equations, combined with dimensionless parameters such as the Rayleigh number. The fluid's thermophysical properties remain constant, except for temperature-dependent density, which is modelled using the Boussinesq approximation to account for buoyancy effects. The governing equations for mass, momentum, and energy conservation are applied to a steady, incompressible, laminar flow in a porous medium.

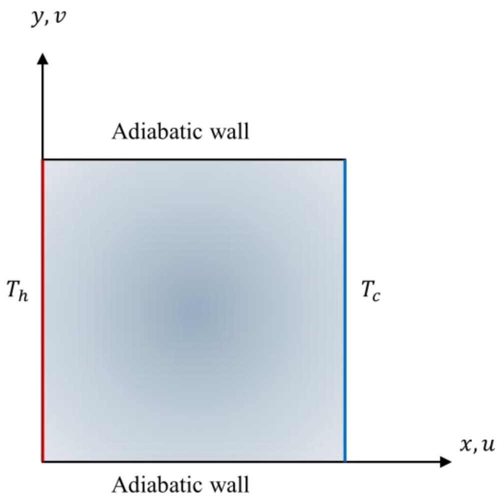


Fig. 1 The physical model configuration

The governing equations (1) to (3) by [8] are:

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

$$\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}=-\frac{g\beta K}{\nu}\frac{\partial T}{\partial x} \tag{2}$$

$$\sigma\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

The equations (1)-(3) were converted into dimensionless forms by using the following dimensionless variables.

$$u=\frac{\partial \psi}{\partial y},\qquad v=-\frac{\partial \psi}{\partial x},\qquad X=\frac{x}{L},\qquad Y=\frac{y}{L},\qquad \theta=\frac{T-T_0}{T_h-T_c}$$

$$\tau=\frac{\alpha t}{\sigma L^2},\qquad \Psi=\frac{\psi}{\alpha},\qquad Ra=\frac{g\beta K\Delta T L}{\nu\alpha}$$

By using the dimensionless variables, equations (1)-(3) are converted to:

$$\frac{\partial^2 \psi}{\partial x\partial y}-\frac{\partial^2 \psi}{\partial x\partial y}=0 \tag{4}$$

$$\frac{\partial^2(\Psi)}{\partial Y^2}+\frac{\partial^2(\Psi)}{\partial X^2}=-Ra\frac{\partial \theta}{\partial X} \tag{5}$$

$$\left(\frac{\partial \theta}{\partial \tau}+\frac{\partial \Psi}{\partial Y}\frac{\partial \theta}{\partial X}-\frac{\partial \Psi}{\partial X}\frac{\partial \theta}{\partial Y}\right)=\left(\frac{\partial^2 \theta}{\partial (X)^2}+\frac{\partial^2 \theta}{\partial (Y)^2}\right) \tag{6}$$

To ensure the dimensionless forms, the obtained equations were compared to dimensionless equations (1) – (3) by [8].

The initial and boundary conditions are as follows:

Initial conditions:

$$u(x, y, 0) = v(x, y, 0) = 0, \qquad T(x, y, 0) = 0$$

Boundary conditions for heated left wall:

$$u(0, y, t) = v(0, y, t) = 0, \qquad T(0, y, t) = 0.5$$

Boundary conditions for cooled right wall:

$$u(1, y, t) = v(1, y, t) = 0, \qquad T(1, y, t) = -0.5$$

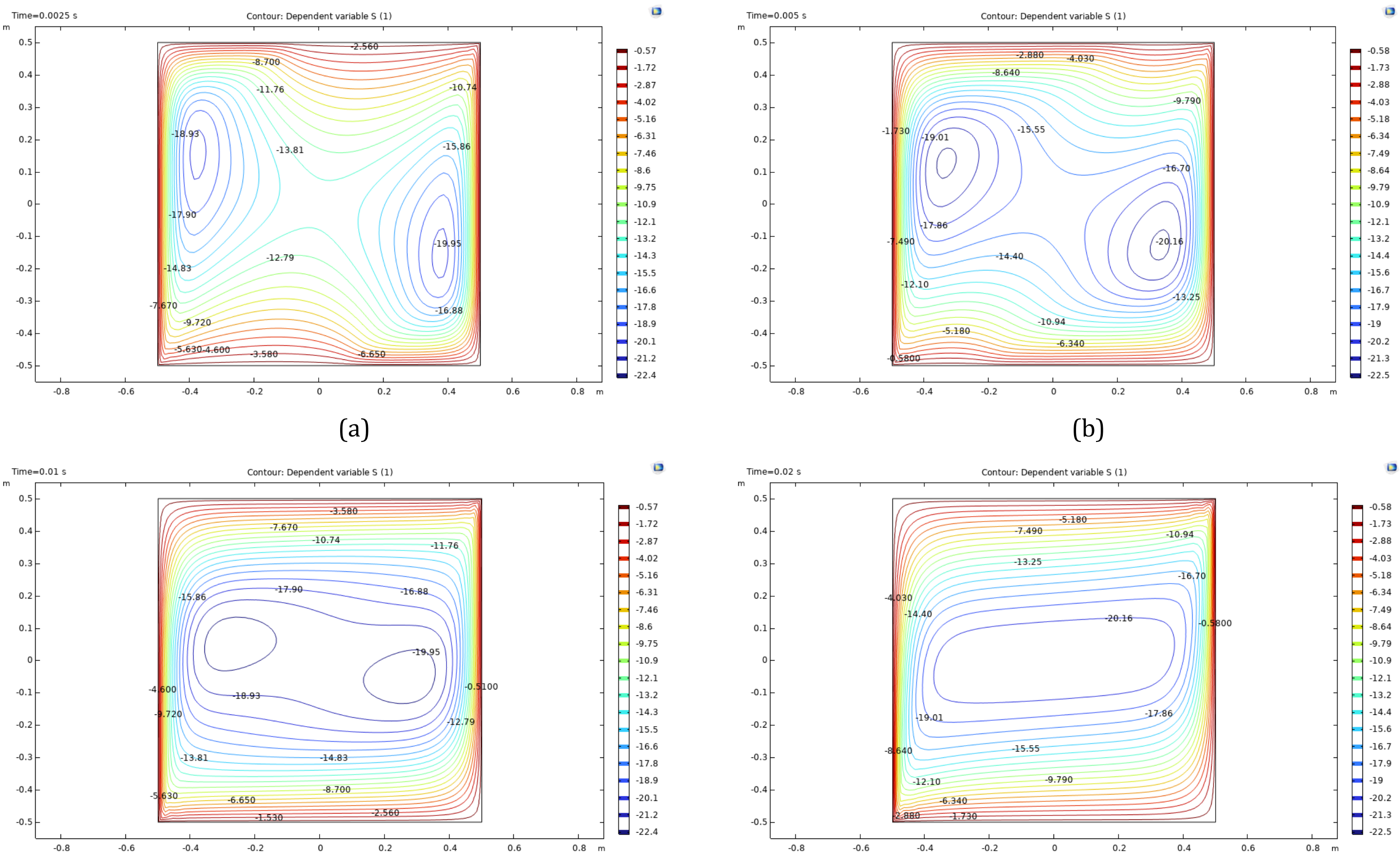
Boundary conditions for adiabatic top and bottom walls:

$$\frac{\partial T(x, L, t)}{\partial y} = 0, \qquad \frac{\partial T(x, 0, t)}{\partial y} = 0$$

3. Results and Discussion

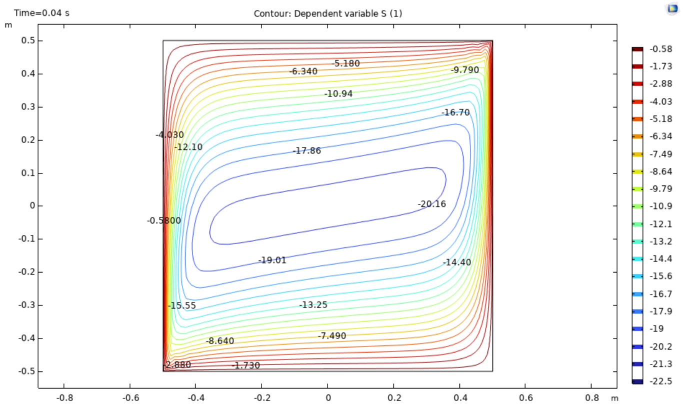
The initial temperature for the heated vertical wall was set to 50°C, while the Rayleigh number (Ra) was fixed to 1000. These values were chosen to observe the transition in heat transfer behaviour from conduction to convection within the porous medium. The streamlines and isotherms were analysed to evaluate the impact of buoyancy-driven forces on fluid motion and temperature distribution in the cavity. The non-dimensional time (τ) is used to generalize the transient behaviour, making it applicable to various physical systems. To relate nondimensional time (τ) to real time (t), the characteristic time scale of the system was used as a reference. It can be converted into real time using a characteristic time scale, which depends on the size of the cavity and the thermal properties of the fluid. This characteristic time represents how quickly heat spreads in the system.

3.1 Streamlines

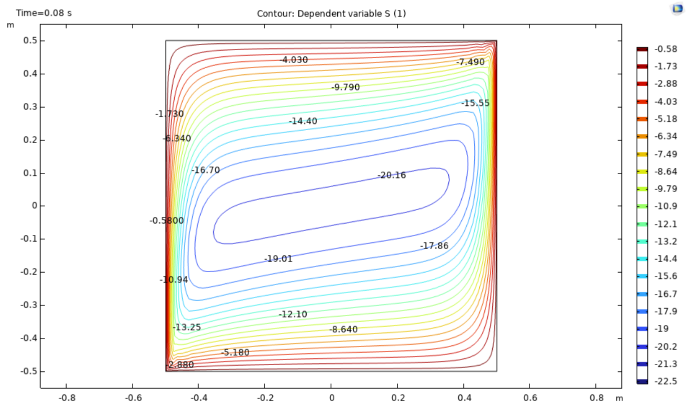


(a) (b)

(c) (d)



(e)



(f)

Fig. 2 Streamlines with Ra = 1000 for various time, τ: (a) τ= 0.0025; (b) τ= 0.005; (c) τ= 0.01; (d) τ= 0.02; (e) τ= 0.04; (f) τ= 0.08

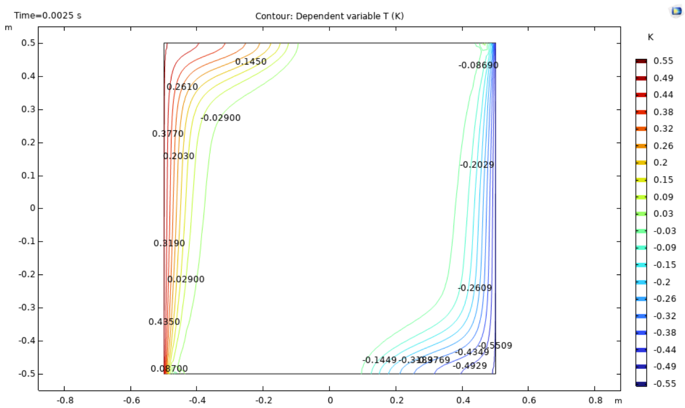
Fig. 2 shows how fluid motion develops over time as heat transfer transitions from conduction to convection within the cavity. Fig. 2(a) shows when τ = 0.0025, the flow is weak and localized with small recirculating zones forming near the top-left and bottom-right corners. These early patterns show how the heated left wall causes fluid to rise while the cooled right wall drives fluid downward. The flow at this stage is gentle and unorganized, reflecting the system's initial adjustment to the sudden temperature changes.

When τ = 0.005 in Fig. 2(b), these recirculating zones begin to grow and spread, and the flow patterns become more pronounced. The buoyancy forces driving the fluid are now more active, leading to visible convective loops near the vertical walls. In Fig. 2(c) shows when τ = 0.01, the streamlines take on a more structured appearance, with distinct circulation patterns developing in the cavity. The motion is stronger, and the flow is more evenly distributed, indicating that convection is now the dominant mode of heat transfer.

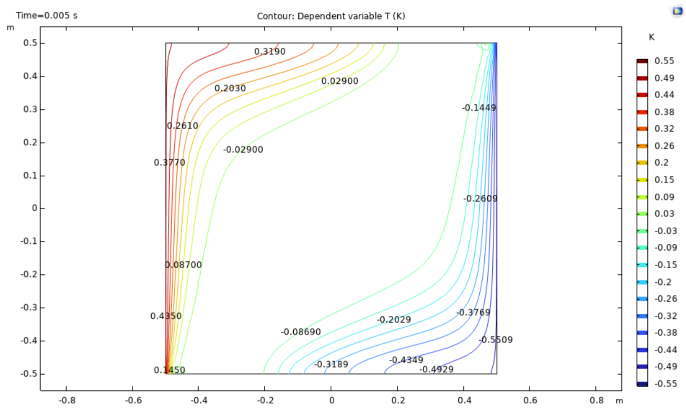
Fig. 2(d) shows at τ = 0.02, the flow patterns stretch further into the cavity, with elongated circulation zones showing how fluid is efficiently moving heat throughout the space. The streamlines become smoother and more stable as the system moves closer to a steady state. At τ = 0.04 in Fig. 2(e), the flow has largely stabilized, and the convective loops are well-defined, symmetrical, and concentrated near the vertical walls.

Finally, Fig. 2(f) at τ= 0.08, the system reaches equilibrium. The streamlines at this stage show fully developed and steady circulation, with the flow efficiently transferring heat from the hot wall to the cold wall. This progression demonstrates how the cavity evolves from a state of minimal motion to one of organized and steady convection.

3.2 Isotherms



(a)



(b)

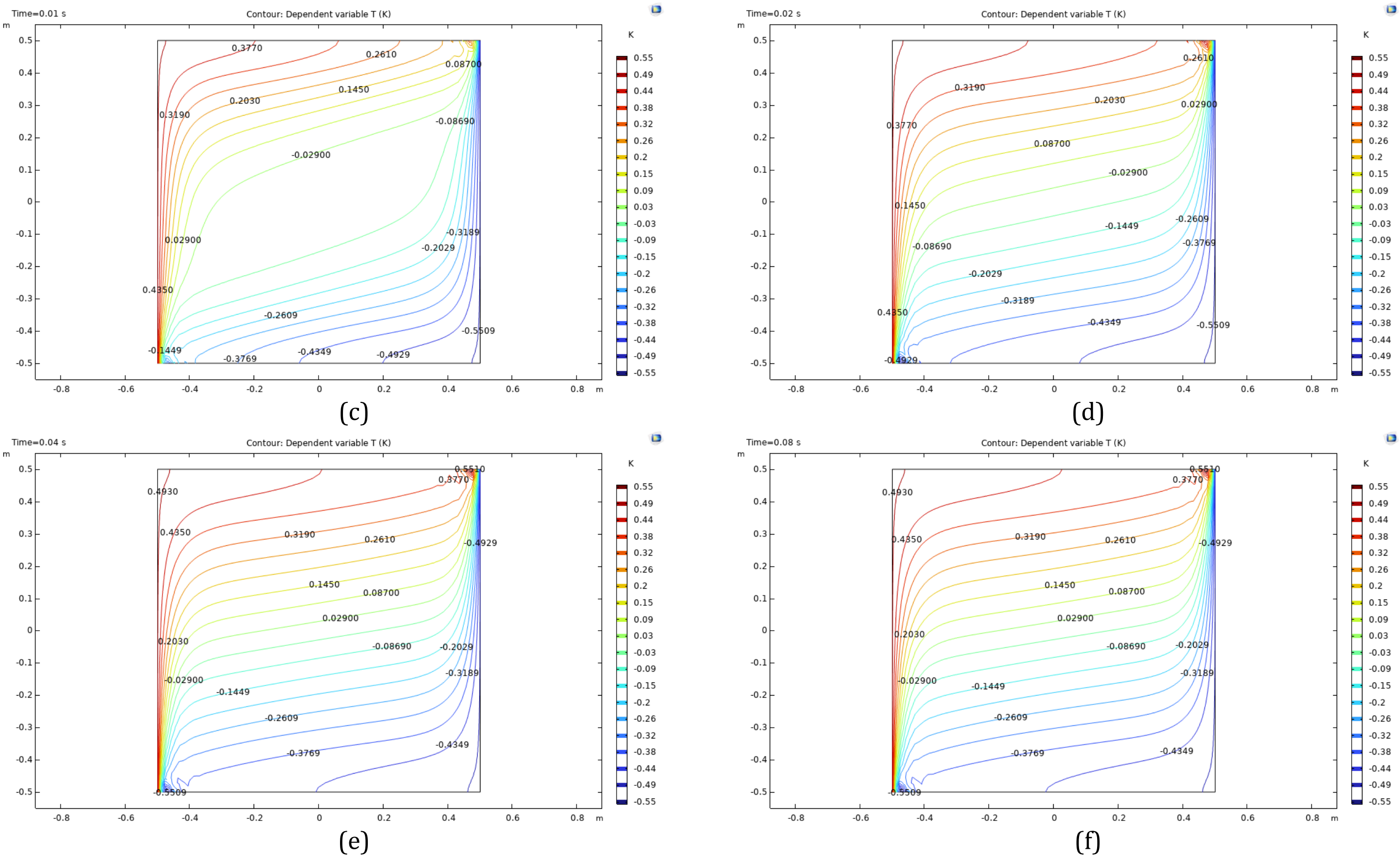


Fig. 3 Isotherms with Ra = 1000 for various time, τ: (a) τ= 0.0025; (b) τ= 0.005; (c) τ= 0.01; (d) τ= 0.02; (e) τ= 0.04; (f) τ= 0.08 s

Fig. 3 displays the distribution of temperature within the cavity over time. Fig. 3(a) shows when $\tau = 0.0025$, the isotherms are nearly vertical and parallel to the heated and cooled walls. This pattern shows that heat transfer is dominated by conduction, with temperature gradients concentrated near the vertical boundaries. At this stage, heat has not yet had time to spread throughout the cavity, and the interior remains largely unaffected by the thermal changes at the walls.

In Fig. 3(b) where τ= 0.005, the isotherms start to curve as convection begins to take hold. Warm fluid rises along the heated left wall while cooler fluid sinks along the right wall, causing the isotherms to distort and move inward. Fig. 3(c) shows when τ= 0.01, this effect becomes more pronounced, with the isotherms forming curved shapes that follow the flow patterns in the cavity. The temperature distribution is no longer confined to the walls, as convection helps spread heat more evenly throughout the cavity.

In Fig. 3(d) where τ= 0.02, the isotherms become smoother and spread further into the cavity, reflecting the growing influence of convective mixing. Fig. 3(e) shows when τ= 0.04, the isotherms stabilize, showing a nearly uniform pattern that signals the system is nearing equilibrium. At this point, the temperature gradients are less steep, and heat is being transferred more effectively by convection. Finally, at τ= 0.08 in Fig. 3(f), the isotherms reach their steady-state configuration and evenly spaced and symmetrical, indicating that the system has achieved a balance between the heat supplied by the hot wall and removed by the cold wall. This steady-state pattern highlights how convection ultimately dominates the heat transfer process, ensuring a uniform temperature distribution across the cavity.

4. Conclusion

This study analysed transient behaviour in a square cavity filled with a porous medium, focusing on the influence of Rayleigh numbers (Ra) by using COMSOL Multiphysics software to simulate and analyse the system. The transient phase is critical for understanding the evolution of heat transfer and fluid flow, as it marks the system's adjustment to temperature gradients and buoyancy forces before reaching equilibrium. In the transient phase, the simulations revealed distinct changes in flow patterns and temperature distributions. At the onset, heat transfer is dominated by conduction, characterized by minimal fluid motion and vertical temperature gradients near the heated and cooled walls. As time progresses, buoyancy forces gradually intensify, leading to the formation of recirculating flow patterns and curved isotherms. These results demonstrate the gradual transition from conduction-dominated to convection-dominated heat transfer during the transient period. The study highlights the significant role COMSOL as it enables accurate modelling of complex fluid flow and heat transfer in porous media, visualizing key parameters like streamlines and isotherms, and efficiently analysing the transient behaviour and effects of Rayleigh numbers.

Future research should explore the effects of different cavity geometries, such as angled or irregular shapes, on the conduction-to-convection transition. Using non-equilibrium thermal models could improve understanding of complex cases, particularly for porous media with diverse properties and higher fluid velocities. Enhanced computational methods and finer-resolution grids may increase accuracy, especially for extreme *Ra*. Experimental validation is also recommended to strengthen confidence in simulation results.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design, solve the governing equation, analysis, and interpretation of results:*** *Kamaruzaman Mustapa, Muhamad Ghazali Kamardan;* ***draft manuscript preparation:*** *Kamaruzaman Mustapa, Muhamad Ghazali Kamardan. All authors reviewed the results and approved the final version of the manuscript.*

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