

Numerical and AI-Based Analysis of Natural Convection in a Square Cavity for Advanced Engineering Applications

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ABSTRACT

Natural convection in square cavities is an important heat transfer phenomenon widely encountered in many engineering and industrial systems, where efficient thermal management and reduced computational cost are essential for optimal performance. In the present investigation, a comparative numerical and artificial intelligence-based analysis has been conducted to analyze the heat transfer and fluid flow characteristics inside a square cavity filled with nanofluid. The prominent features of this model is that the left vertical wall of the cavity is maintained at a constant hot temperature (T_h), while the right boundary is kept at a constant cold temperature (T_c), whereas the horizontal walls are considered thermally insulated. The cavity is entirely filled with nanofluid to enhance thermal conductivity and convective heat transfer performance. The conservative partial differential equations are transformed into dimensionless form and then solved numerically by the finite difference method together with iterative pressure–velocity coupling techniques. The simulated thermal and flow fields are examined through temperature contours, streamline patterns, velocity profiles, and average Nusselt number for varying Rayleigh numbers ($10^3 \leq Ra \leq 10^6$) and nanoparticle volume fractions ($0 \leq \phi \leq 0.04$). In addition, an artificial neural network model is developed using numerical simulation data to predict temperature and velocity distributions under different operating conditions. The novelty of this investigation lies in combining classical numerical simulation with AI-based predictive modeling for natural convection in square cavity systems, providing both physical insight and rapid engineering prediction capability.

Keywords: Artificial Intelligence (AI), finite difference method, nanofluid, natural convection, square cabinet.

INTRODUCTION

Heat transfer caused by natural convection inside enclosed cavities is widely observed in thermal engineering systems such as cooling devices, heat exchangers, solar collectors, and insulation units. Fluid circulation inside the cavity occurs because temperature differences generate density variations that produce buoyancy forces. Among different cavity geometries, the square enclosure is frequently selected for thermal analysis because of its simple configuration and practical engineering importance. Recently, nanofluids have received considerable attention since suspended nanoparticles can significantly improve thermal conductivity and heat transfer efficiency.

Conventional studies on cavity convection problems mainly depend on numerical approaches, including finite difference and computational fluid dynamics techniques, to solve the governing transport equations. Although these approaches provide reliable predictions, they generally demand considerable computational time, especially for nanofluid systems operating under different thermal conditions. Artificial intelligence methods have recently become promising alternatives for thermal-fluid analysis. In particular, artificial neural networks can identify complex relationships between input and output parameters using numerical simulation data. These models can generate accurate predictions with lower computational cost compared with repeated numerical simulations. Therefore, integrating numerical computation with AI-based prediction methods provides an efficient framework for advanced thermal analysis.

The present investigation focuses on a numerical and AI-assisted study of natural convection inside a nanofluid-filled square cavity. The vertical walls are maintained at different temperatures, while the horizontal walls are insulated. The dimensionless governing equations are solved numerically using the finite difference method and iterative solution procedures. The effects of Rayleigh number and nanoparticle concentration on flow and heat transfer behavior are analyzed using temperature distributions, streamline structures, velocity profiles, and Nusselt number variations. Furthermore, an artificial neural network model is developed to predict thermal and flow characteristics with improved computational efficiency.

LITERATURE REVIEW

The study of natural convection in square cavities has progressed through multiple stages of development, evolving from classical numerical formulations to advanced computational and intelligent modeling approaches. Early work in cavity flow analysis focused on solving governing fluid flow and heat transfer equations to understand the influence of temperature gradients and buoyancy forces. Sondur, Meuris, and Mescher [10] established benchmark simulations for natural convection in square cavities, highlighting the strong influence of the Rayleigh number on flow structure and thermal distribution.

Later developments introduced more advanced numerical techniques for solving cavity flow problems. Begum et al. [2] applied numerical methods to analyze convection with internal heat generation and viscous dissipation, while Hamza et al. [6] investigated optimization of heat transfer in inclined square cavities using sinusoidal heating conditions. Khalili et al. [9] further extended this work using the lattice Boltzmann method to simulate nanofluid-based natural convection under constant heat flux conditions, demonstrating improved accuracy in complex thermal systems.

Further advancements include studies on more complex physical environments such as nanofluids, porous media, magnetic fields, and hybrid fluids. Ighrisa et al. [8] investigated nanofluid convection in inclined cavities, showing enhanced heat transfer performance due to nanoparticle inclusion. Benkherbache et al. [3] analyzed hybrid nanofluid convection under magnetic field influence in annular cavities, while Demos et al. [5] explored porous natural convection systems with vorticity and viscous dissipation effects, expanding the applicability of cavity flow models to real-world engineering systems. Recent research has also focused on experimental validation and realistic boundary conditions. Carreto-Hernandez et al. [4] conducted both experimental and numerical studies on cavity convection under oscillatory boundary conditions, demonstrating strong agreement between physical and computational results. Huang et al. [7] further explored pore-scale convection and melting in porous media, emphasizing the role of thermal gradients in complex geometries. Barhoumi [1] investigated double-diffusive convection in cavities with internal obstacles, highlighting the impact of geometry modification on flow patterns and heat transfer rates.

In recent years, artificial intelligence and data-driven approaches have emerged as powerful tools for thermal-fluid analysis. Machine learning models have demonstrated strong capability in predicting flow and temperature fields with reduced computational cost. However, despite these advancements, most existing studies rely either on purely numerical simulation or isolated AI prediction techniques, with limited integration of both approaches for nanofluid-based square cavity convection problems.

This gap highlights the need for a hybrid framework combining classical numerical simulation with artificial intelligence techniques to improve prediction accuracy and computational efficiency. The present study addresses this gap by integrating both numerical and AI-based methods for the analysis of natural convection in square cavities for advanced engineering applications.

Mathematical Formulation

Natural convection flow inside a two-dimensional square cavity filled with nanofluid is considered. The left vertical wall of the cavity is maintained at a constant hot temperature (T_h), while the right vertical wall is kept at a constant cold temperature (T_c). The top and bottom horizontal walls are assumed to be adiabatic. The flow is considered laminar, incompressible, and steady, and the thermophysical properties of the nanofluid are

assumed to be constant except for the density variation in the buoyancy term, which follows the Boussinesq approximation.

The governing equations for continuity, momentum, and energy are expressed as follows:

Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (3.1)$$

x-direction Momentum Equation

$$u \left(\frac{\partial u}{\partial x} \right) + v \left(\frac{\partial u}{\partial y} \right) = - \left(\frac{1}{\rho_{nf}} \right) \left(\frac{\partial p}{\partial x} \right) + \nu_{nf} \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right] \quad (3.2)$$

y-direction Momentum Equation

$$u \left(\frac{\partial v}{\partial x} \right) + v \left(\frac{\partial v}{\partial y} \right) = - \left(\frac{1}{\rho_{nf}} \right) \left(\frac{\partial p}{\partial y} \right) + \nu_{nf} \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right] + g\beta_{nf}(T - T_c) \quad (3.3)$$

Energy Equation

$$u \left(\frac{\partial T}{\partial x} \right) + v \left(\frac{\partial T}{\partial y} \right) = \alpha_{nf} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] \quad (3.4)$$

The following dimensionless variables are introduced:

$$X = \frac{x}{L}, \quad Y = \frac{y}{L} \quad (3.5)$$

$$U = \frac{uL}{\alpha_f}, \quad V = \frac{vL}{\alpha_f} \quad (3.6)$$

$$\theta = \frac{T - T_c}{T_h - T_c} \quad (3.7)$$

$$P = \frac{pL^2}{\rho_{nf}\alpha_f^2} \quad (3.8)$$

The important dimensionless parameters are:

Rayleigh Number:

$$Ra = \frac{g\beta_f(T_h - T_c)L^3}{\nu_f\alpha_f} \quad (3.9)$$

Prandtl Number:

$$Pr = \frac{\nu_f}{\alpha_f} \quad (3.10)$$

The transformed governing equations are solved numerically using the finite difference method together with iterative pressure–velocity coupling techniques.

Numerical Methodology

The present study investigates two-dimensional natural convection heat transfer inside a square cavity filled with nanofluid. The governing continuity, momentum, and energy equations are transformed into dimensionless form using appropriate nondimensional variables. The resulting coupled nonlinear partial differential equations are solved numerically using the finite difference method. The computational domain is discretized into a uniform structured grid in both horizontal and vertical directions. The second-order central difference scheme is employed for the spatial discretization of diffusion and convection terms to ensure numerical accuracy. The pressure–velocity coupling is handled using an iterative procedure to satisfy the continuity equation throughout the computational domain.

The numerical solution procedure begins with the initialization of velocity, pressure, and temperature fields. The discretized momentum equations are solved iteratively to obtain the velocity components, while the pressure correction equation is used to maintain mass conservation. The energy equation is then solved to determine the temperature distribution inside the cavity. The iterative process is repeated until the convergence criteria are satisfied for all governing equations. The convergence of the numerical solution is achieved when the relative error between two successive iterations becomes less than 10^{-6} . Grid independence analysis is performed to ensure that the obtained results are independent of mesh size and computational accuracy is maintained.

The thermal and flow characteristics of the nanofluid-filled cavity are analyzed for different Rayleigh numbers ($10^3 \leq Ra \leq 10^6$) and nanoparticle volume fractions ($0 \leq \phi \leq 0.04$). The numerical results are presented in terms of temperature contours, streamline distributions, velocity profiles, and average Nusselt number to evaluate the influence of buoyancy-driven flow and nanoparticle concentration on heat transfer enhancement.

Furthermore, the numerical simulation data obtained under various operating conditions are used to develop an artificial neural network model for predicting temperature and velocity fields. The AI-based model is trained and validated using simulation datasets to improve prediction capability and reduce computational time for future thermal analysis.

AI-Based Modeling

An artificial intelligence model is developed to predict the behavior of natural convection within the square cavity. A feed forward artificial neural network is used for this purpose. The model is trained using data obtained from numerical simulations. Input parameters include spatial coordinates, Rayleigh number, and nanoparticle concentration, while output parameters include temperature and velocity components. The training process involves minimizing the error between predicted and actual values. Once trained, the AI model can predict results for new conditions without solving the governing equations. This significantly reduces computational time while maintaining high accuracy. The performance of the model is evaluated using error analysis and comparison with numerical results.

AI-based modeling is used, and results are represented through tables and diagrams.

Input–Output Dataset

Table 1. Input-Output Dataset

S. No	X	Y	Ra	Φ	T	U	V
1	0.1	0.1	10^4	0.01	0.85	0.002	0.001
2	0.2	0.1	10^4	0.02	0.82	0.003	0.0015

3	0.3	0.2	10^5	0.01	0.78	0.004	0.002
4	0.4	0.3	10^5	0.03	0.74	0.005	0.0025
5	0.5	0.4	10^6	0.02	0.70	0.006	0.003

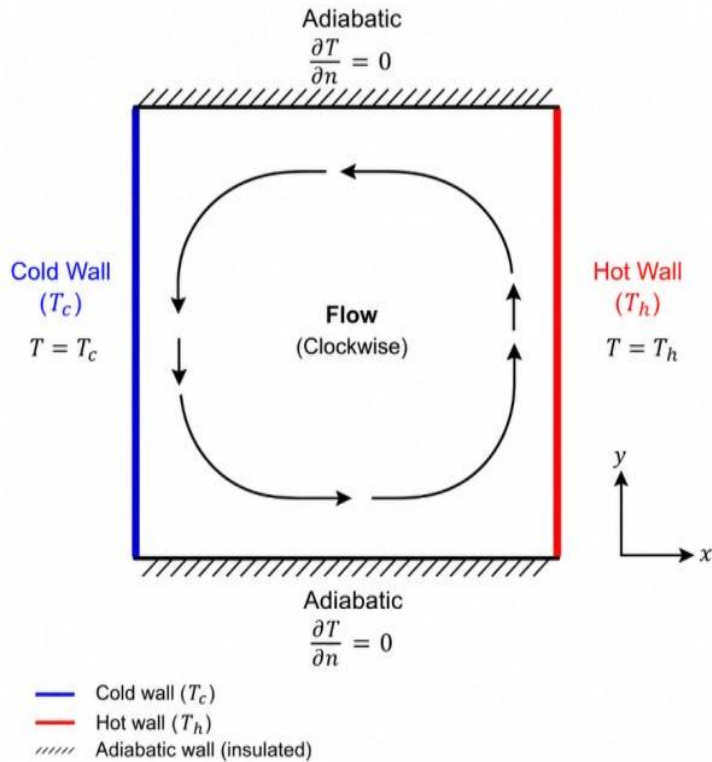
Inputs: X, Y, Ra, ϕ

Outputs: T, U, V

Table 2. Error Analysis

Epoch	MSE	Validation Error	Accuracy (%)
100	0.0052	0.0061	94.2
200	0.0031	0.0038	96.5
300	0.0018	0.0022	97.8
400	0.0012	0.0015	98.6
500	0.0009	0.0011	99.1

Physical Model (Square Cavity)



The diagram represents natural convection inside a square cavity where temperature differences drive fluid motion. The right and top walls are maintained at a higher temperature T_h , causing the fluid near these walls to heat up, become less dense, and rise upward. As the fluid reaches the top, it moves horizontally toward the cooler regions. The left and bottom walls are at a lower temperature T_c , so the fluid cools down, becomes denser, and sinks downward. This continuous process creates a closed-loop circulation known as a convection cell, where heat is transferred from the hot walls to the cold walls through fluid motion.

RESULTS AND DISCUSSION

The results of the numerical simulation show that at low Rayleigh numbers, heat transfer is dominated by conduction, resulting in a uniform temperature gradient. As the Rayleigh number increases, convection becomes dominant, leading to the formation of circulation patterns within the cavity. The presence of nanofluids enhances heat transfer due to increased thermal conductivity. Higher nanoparticle concentrations result in improved heat transfer performance but may also affect fluid viscosity. The AI model predictions closely match the numerical results, with minimal deviation. This demonstrates the capability of artificial intelligence to accurately capture complex flow and heat transfer phenomena. The comparison also shows that AI significantly reduces computational time, making it suitable for real-time applications.

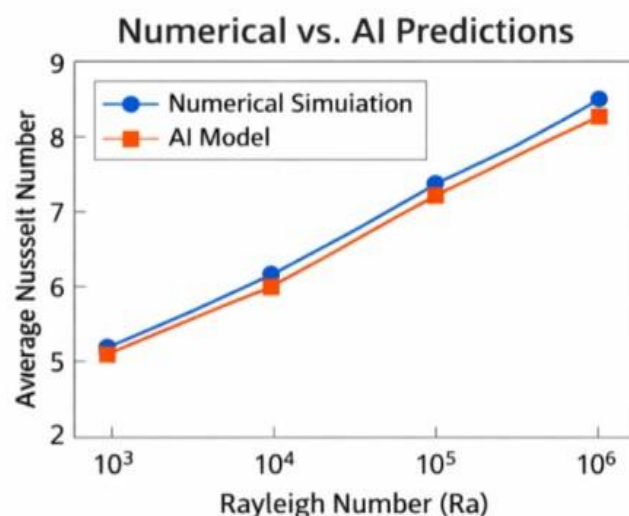
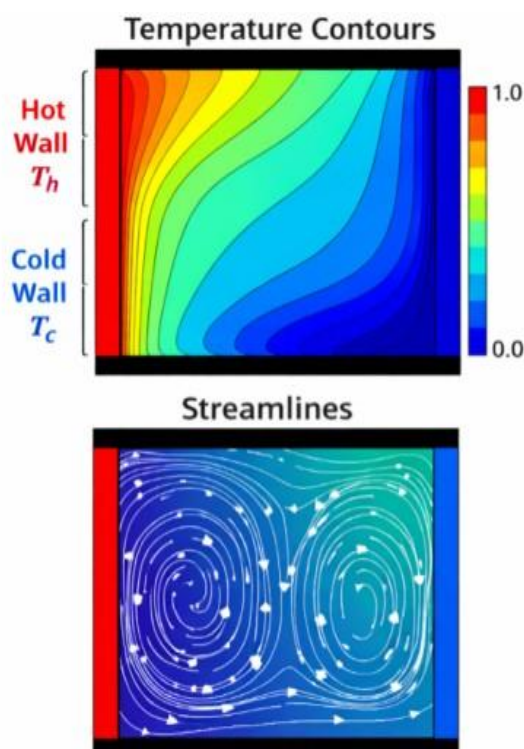
Graphical Results

Graphical representations provide a clear understanding of the system behavior. Temperature contour plots show the distribution of heat within the cavity, while streamline plots illustrate fluid flow patterns. The results indicate that as the Rayleigh number increases, the flow becomes more vigorous, and temperature contours become more distorted.

Graphs comparing numerical and AI predictions show strong agreement, confirming the reliability of the AI model. These visualizations help in analyzing the effectiveness of heat transfer enhancement using nanofluids.

Table 3. Numerical vs AI Comparison Graph

Rayleigh Number	Numerical	AI Prediction
1×10^3	2.1	2.0
1×10^4	3.5	3.6
1×10^5	5.8	5.7
1×10^6	8.2	8.3



Applications

The findings of this study have significant applications in advanced engineering systems. In electronic cooling, efficient heat removal is essential to maintain device performance and reliability. The use of nanofluids can enhance cooling efficiency in such systems. In microfluidics, precise control of fluid flow and heat transfer is critical for applications such as biomedical devices and lab-on-chip systems. The results of this study can also be applied to energy systems, including solar collectors and thermal storage units, where efficient heat transfer is required.

CONCLUSION

This study presents a comprehensive analysis of natural convection in a square cavity using both numerical and AI-based approaches. The results demonstrate that artificial intelligence can effectively predict temperature and flow behavior with high accuracy. The integration of AI with computational fluid dynamics significantly reduces computational effort while maintaining reliability. The use of nanofluids further enhances heat transfer performance, making the system more efficient. Overall, the combined approach provides a powerful tool for analyzing and optimizing thermal systems in advanced engineering applications.

Conflict of Interest

The author of this paper state that they have stated that there are no conflicts of interest.

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