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On the natural convection of nanofluids in diverse shapes of enclosures: an exhaustive review

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Abstract

The ultimate goal of the present review paper is to summarize and discuss the findings of the most recently published literature on natural convection of nanofluids in various enclosures. The review covers five different geometries of enclosures: square, circular, triangular, trapezoidal, and unconventional geometries. The core findings of the reviewed papers are summarized and tabulated in a table. Moreover, the relation between the thermophysical properties and the way they affect each other is demonstrated for different geometries of enclosures. Various numerical methods, such as finite difference, finite volume, and finite element methods, as well as different microscopic models, such as single-phase and two-phase models, are considered in this review.

Keywords Natural convection · Exhaustive review · Cavity · Nanofluid · Numerical simulation · Thermophysical properties

Abbreviations

Nu	Nusselt
Ra	Rayleigh
Ha	Hartmann
Le	Lewis
Pr	Prandtl
LBM	Lattice Boltzmann Method
RSM	Response surface method
EMM	Eulerian mixture model
EEM	Eulerian–Eulerian model
MHD	Magnetohydrodynamic
Gr	Grashof

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Introduction

It is known that low thermal conductivity and critical heat flux would be considered as the main weaknesses of conventional fluids, such as oil, water, and ethylene glycol (EG) [1–3]. Masuda et al. [4] are among the first researchers who tried to enhance the thermal conductivity of conventional fluids by adding nanosized particles that possess higher thermal conductivity compared to the base fluids. Literature shows that Maxwell [5] introduced the very first idea of the suspensions of solid particles into conventional fluids to enhance the heat transfer in the nineteenth century. However, technological limitations did not let him approach nanosize particles. After the pioneering research on nanofluids, researchers started to conduct different studies to explore various aspects of nanofluids, such as the dynamic

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viscosity [6–8], thermal conductivity [9–11], heat transfer performance [12–14], applications of artificial intelligence in predicting different properties of nanofluids [15–17], and applications of nanofluids [18–20]. There are also some review papers that reviewed and summarized the findings of researchers on different aspects of nanofluids [21–23].

Another important factor is the size of the mixed solid particle into the base fluids. It is known that the microparticles settle rapidly in the base fluids, which leads to increasing the viscosity of the fluids and increasing the pressure drop [24–26]. The idea of using nanoparticles to improve heat transfer was first introduced by Choi and Eastman [27]. They used nanoparticles with the diameters of less than 100 *nm* in water to enhance the effective thermal conductivity of water.

There are three categories of heat transfer in nanofluids: natural convection, mixed convection, and forced convection [28, 29]. Dahani et al. [28] studied forced convection flow in a square-lid-driven cavity, and they used the lattice Boltzmann method to solve the governing equations. They demonstrated that water–Ag nanofluid is useful in enhancing the heat transfer rate, and the average Nusselt (Nu) number is a decreasing function of the Rayleigh (Ra) number. On the other hand, by changing the Ra number, they stimulated the interaction between conduction and forced convection. Chen et al. [30] demonstrated that after nanoparticles are added into the base fluid, natural convection streamlines and temperature contours transform slightly. However, when it came to mixed convection, the changes were significant regarding the force convection effects. The advantages of natural convection compared to forced convection are lower noise, lower power consumption, and lower required maintenance of the systems that utilize natural convection. These systems also do not need external sources like pump and fan to provide fluid flow motion; this phenomenon occurs only by the effect of variation in density. Sheikholeslami et al. [31] studied MHD free convection of Al_2O_3-water by considering the Brownian motion and thermophoresis effects in an enclosure. They used the headline visualization technique for the intensity and direction of heat transfer and studied the effect of Hartmann (Ha) and Lewis (Le) numbers. In another study, Ashorynejad and Hoseinpour [32] investigated the natural convection inside a porous enclosure. They utilized the method of lattice Boltzmann to calculate entropy generation and average Nu number.

Cavities and enclosures are becoming of the most interesting subject among different industries like energy, HVAC, solar systems, electronic components, double-pane windows, and biomechanics. There are some techniques to enhance heat transfer in enclosures. Firstly, if flow geometry transforms, the convection heat transfer considerably increases. Thus far, various cavity shapes such as rectangular [33], triangular [34], trapezoidal [35], and other shapes are studied. Sun and pop [36] studied the free convection in a cavity with a triangular shape and equipped with a porous medium. They used three different nanoparticles to study temperature characteristics and average Nu number. Moreover, they studied different boundary conditions, such as wavy wall [37], heat generation [36], heat flux [37], and wall temperature [38]. Hatami et al. [39] studied how to transfer heat by natural convection in a wavy circular cavity. While a cosine function was presumed for the equation of the inner wall, the Nu number and also heat transfer increased rapidly. Thirdly, another method to boost heat transfer in cavities is to improve the fluid's thermal conductivity [40]. There is a wide variety of applications for the magnetic field inside enclosures such as the power and cooling industry, chemical industry, nuclear reactors, and growth of the crystal in liquids [41]. Nemati et al. [42] analyzed the effects of the magnetic field on the natural convection of a nanofluid in a rectangular cavity. They illustrated how the magnetic field decreases the circulation of flow inside the cavity. As the magnetic field becomes stronger, the convection heat transfer reduces; then, the conduction heat transfer becomes the dominant mode of heat transfer.

There are different numerical methods to solve natural convection problems. Finite difference, finite volume, and finite element methods have been developed to discrete the governing equations [8]. Lattice Boltzmann method (LBM) is also a powerful method to prognosticate the exact behavior for various relevant problems [43, 44]. Sheikholeslami et al. [45] studied the LBM to simulate the MHD natural convection in a cylindrical enclosure. They also investigated the consequence of nanoparticle Ha number, the Ra number, and the volume fraction. Natural convection heat transfer in a wavy circular cavity is investigated by Hatami et al. [46]. The response surface method (RSM) is used to discover the geometry, which is optimum for the wavy wall, and also FEM and RSM solved and optimized the outcomes. They found that when the amplitude quantity is 0.3, and the figure of the undulations is 12, it is the best case between the tested cases. The proposed method was assumed to have extensive application in time-efficient optimization of heat transfer for irregular geometries.

Analytically, there are two microscopic approaches to model nanofluid heat and flow transfer: single-phase model and two-phase model. The first model considers base fluid and nanoparticles as a single homogeneous liquid considering its useful attributes [47, 48]. The second one looks at nanofluid as a non-homogenous mixture of base fluid and nanoparticles and handles Navier–Stokes equations for base fluid and particles by two different methods. These methods are the Eulerian mixture model (EMM) and the Eulerian–Eulerian model (EEM). EMM method solves momentum and energy equations for a mixture of the phases and continuity equation for each of the phases. However, the

EEM method solves continuity, momentum, and energy equations for each phase.

Although two-phase models are more accurate, the single-phase model has acceptable results in low volume concentrations [49, 50].

The main idea of the present review paper is to present an exhaustive review of the works done in natural convection heat transfer of nanofluids in various enclosures. This review provides valuable information about the approaches utilized thus far and demonstrates a suitable overview of weaknesses, strengths, and, more importantly, the astonishing results of studies done in this field. To the best of the authors' knowledge, although studies are done to overview the forced and mixed flow convection of nanofluid in enclosures, no one has studied the overview of natural flow convection of nanofluids inside enclosures. In the following sections, the literature on natural convection of nanofluids in different enclosures will be presented and discussed. Moreover, the trend of the published papers during recent years, the most used nanoparticles, and the most frequent shapes will be presented graphically in order to gain a vivid insight of the overall activities which are done in this field of expertise.

Natural convection of nanofluids in enclosures

There is a strong possibility that the first investigation about natural convection of nanofluids in an enclosure was done by Walker and Homsy [51]. They studied natural convection in a porous cavity. The cavity was differentially heated, and the solutions were governed by two dimensionless parameters: cavity aspect ratio and Darcy–Rayleigh number. Moreover, the flow was considered as steady two-dimensional. They were concerned with the changes of Nu number with respect to changes in Darcy–Rayleigh number and cavity aspect proportion as well.

In the following sub-sections, the works done by different authors on natural convection heat transfer and thermophysical properties of nanofluids in different enclosures will be reviewed and discussed.

At natural convection heat transfer of nanofluid, conductivity and viscosity play the important role. When the nanoparticles are added to pure fluid, the conductivity and viscosity are increased. So if the conductivity shows more role on heat transfer than viscosity, then the Nu number is increased, and conversely, if viscosity is dominate, the Nu decreases.

Modeling approaches

As it is mentioned, there are different approaches to model heat transfer, and especially natural convection of nanofluids in cavities. Most of the work which is done in the literature uses single-phase method to model nanofluid equations [52–59]. This approach considers nanoparticles and base fluid as one liquid with effective physical properties. Matori et al. [60] used a single-phase approach to model incompressible and laminar nanofluid in an Π-shaped cavity with a hot obstacle at the upper wall with the application in electric devices and ventilation. Moreover, they used lattice Boltzmann method to simulate the fluid flow and heat transfer. In computational fluid dynamics, lattice Boltzmann method is a novel approach that solves flow and thermal equations by the theory of kinetic energy of particles and distribution functions and finally finds the velocity, temperature, and pressure. Sobhani et al. [61] utilized this method coupled with Taguchi approach (which is beneficial in decreasing the time and cost of simulations and total runs) for the first time to find the optimal condition of the natural convection heat transfer parameters in a cavity with Al_2O_3 nanofluid with the single-phase approach. Although single-phase and two-phase approaches have different outcomes and based on our knowledge and literature, it is not clear which one is better to model different nanofluids with various boundary conditions; there are just few works done to compare these two approaches [62, 63]. Etesami et al. [64] compared single- and two-phase models for $Fe_3O_4^-$ ethylene glycol nanofluid around the platinum wire. Their results demonstrated that two-phase model could better predict experimental data due to considering the velocity of each phase in the model. They also considered the effects of electric field on heat transfer instead of magnetic field, and there are just few works done to apply the effects of electric field. They firstly modeled laminar and steady-state single-phase approach to model the nanofluid by considering the thermophysical properties of base fluid and nanoparticles. On the other hand, they used EEM model as a two-phase approach by some assumptions such as the same pressure field for both phases and spherical particles. They concluded that for all concentrations of nanofluid, two-phase approach could better predict experimental data. Two-phase approach is rarely done in the literature, and more work needs to be done in this regard. This approach considers several approaches such as the Brownian motion, layering at the solid/liquid interface, ballistic phonon transport through particles, nanoparticle clustering, and the friction between fluid and solid particles. Vahedi et al. [65] used Eulerian–Eulerian two-phase model to simulate the nanofluid in heat exchanger. They presumed that not only the coupling between phases is enough strong and nanoparticles follow the flow behavior, but also two phases are inter-penetrating which means each phase (fluid and solid) has its own velocity and volume concentration. Moreover, they utilized SIMPLEC algorithm and the turbulence model of $k-\varepsilon$. Their results demonstrated that using nanoparticles and turbulator increases the heat transfer performance of heat exchanger and the similar performance can be achieved by smaller and cheaper heat exchanger. According to the literature of this paper, there are few works done to investigate the natural convection of nanofluids in enclosures with a two-phase approach. Esmaili et al. [66] investigated the mixed convection and pressure drop of a nanofluid in a rectangular channel with two-phase approach. They assumed that the flow is turbulent with constant heat flux boundary condition. One of the most important types of flow is non-Newtonian nanofluids which are rarely investigated in cavities. Siavashi et al. [67] studied a two-phase non-Newtonian nanofluid inside porous square enclosure with a rotating cylinder.

All in all, single-phase approach is more widely used by researchers to model natural convection of nanofluids in cavities due to its simplicity and being time and cost-effective. According to the works studied in this review, just some of the works in literature are conducted to compare single-phase and two-phase approaches which are not enough to fully understand the differences and applicability of these two approaches in various cavities. On the other hand, just few researches are done regarding two-phase approaches and most of them are about mixed or forced convection but not natural convection.

Square enclosures

Square and rectangular enclosures are the most widely studied shapes by researchers in natural convection of nanofluids. Their most applications are in electronic devices, solar systems, and dual-pane windows. The fluid flow within these enclosures is considered transient or steady state. Yu et al. [68] studied transient natural convection of aqueous nanofluids in a differentially heated cavity. Teamah et al. [69] studied laminar steady-state flow regime and investigated the effects of magnetic field on natural convection behavior of nanofluid in the presence of heat generation or absorption. Moreover, the analysis in these enclosures is done experimentally, numerically, and theoretically. Ho et al. [70] did an experimental study on natural convection of alumina–water nanofluid in square enclosures with different sizes. In their analysis, they tested various volume fractions of alumina nanoparticles. Ho et al. [71] studied the effects of uncertainties on dynamic viscosity and thermal conductivity of alumina–water nanofluid under natural convection process inside an enclosure. They performed the simulations in different ranges of Ra number (10^3–10^6) and solid concentrations ($\varphi = 0$–4 vol.%). Figures 1 and 2 demonstrate the configuration of the square geometry they used to model their nanofluid. They concluded that the averaged Nu number ($Nu_{ave.}$) of the hot wall has a monotonic alteration with φ in various Ra numbers, as shown in Fig. 3. This figure also reveals that the Nu_{ave} does not boost all the time by adding nanofluid, and it depends on the Ra number and the formula for the effective dynamic viscosity. Bhuiyana et al. [72] studied natural convection in a square-shaped cavity, which was heated at the bottom wall. The base fluid was water, and they used the Galerkin weighted method of finite element formulation. The calculations were done regarding Ra number in the range of 10^3–10^6 and the solid volume fractions of $0 \le \phi \le 0.2$ for different nanoparticles. The schematics of square geometry, which is used in their study, is shown in Fig. 4. They concluded that $Nu_{ave.}$ along the hot wall increases as Ra number changes from 10^3 to 10^6 and also for higher values of φ. These results are shown in Fig. 5. Some of their substantial results were as follows:

- For higher values of φ and Nu_{ave}., the rate of heat transfer is augmented.
- The average temperature goes down by boosting the values of φ and Nu_{ave}.
- Nanoparticles that have the lowest thermal conductivity cause the lowest increase in heat transfer.

Mahian et al. [73] compared experimental and theoretical outputs of their analysis on natural convection of SiO_2 nanoparticles laden in water in a square cavity. The next important factor which is studied in square cavities is porous media and porous obstacles. Saeid et al. [38] investigated the natural convection in a square porous cavity with spatial sinusoidal temperature variation in one of the side walls. They utilized the Darcy model and finite volume method, which is based on the QUICK scheme for solving non-dimensional governing equations. They concluded that the local Nu number varies sinusoidally with the variation in hot wall temperature. Moreover, they concluded that the average Nu number changes sinusoidally by increasing the wave number.

Some studies focused on comparing the effects of nanoparticles (type and size) on overall heat transfer performance in square cavities. Ma et al. [74] considered the effects of porous obstacle (Sierpinski carpets) on MHD natural convection in a square cavity with three different temperature boundary conditions on the hot walls. Oztop et al. [75] studied heat transfer as a consequence of buoyancy force in a square enclosure, which was heated partially. They used the finite element technique to solve the governing equations and utilized different nanoparticles. The most critical parameters and their ranges were volume fraction of nanoparticles ($0 \le \varphi \le 0.2$), Ra number ($10^3 \le Ra \le 5 \times 10^5$), the height of heater ($0.1 \le h \le 0.75$), and aspect ratio ($0.5 \le \alpha \le 2$). In conclusion, while higher φ is used for the whole range of Ra number, the Nu_{ave}. increases. Other findings were as:

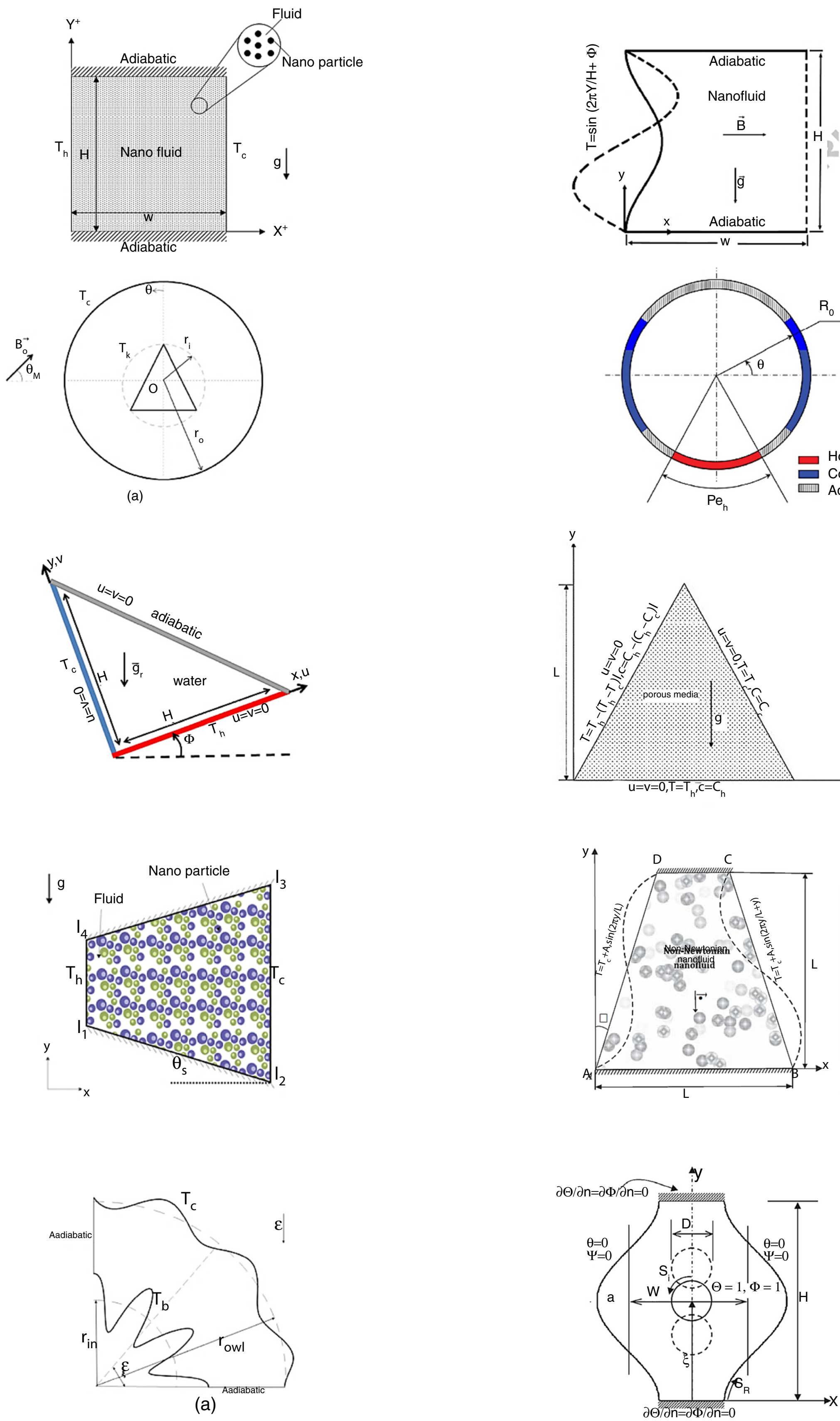


Fig. 1 Summary of geometries that have been used

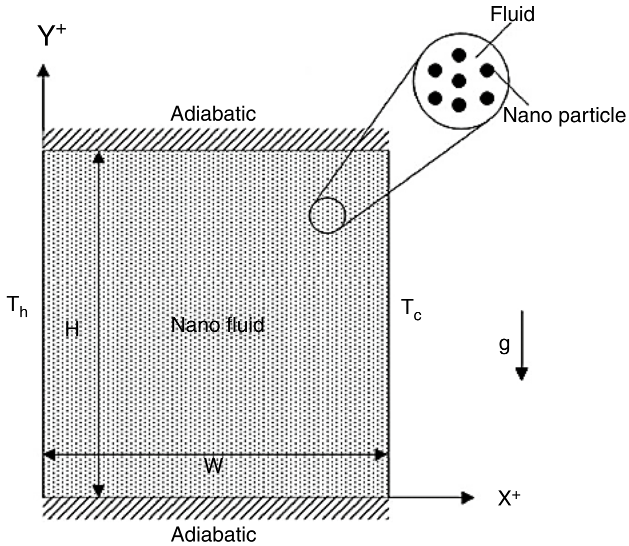


Fig. 2 Schematic view of the physical configuration and coordinate system [52]. (Reprinted with the permission of the publisher)

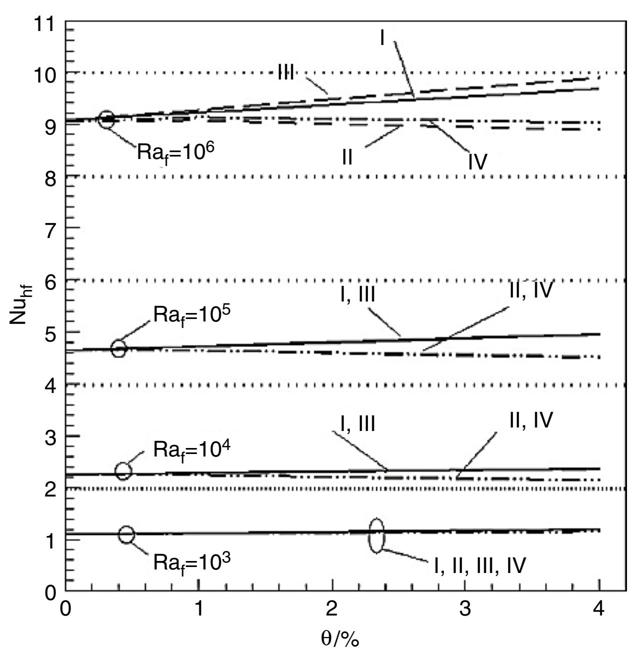


Fig. 3 Variation in average Nu number with volumetric fraction for various Ra numbers and different models of dynamic viscosity [52]. (Reprinted with the permission of the publisher)

- If the value of Ra number and the size of heater increase, the heat transfer enhances (other parameters are assumed to be fixed).
- The type of nanoparticle plays a crucial function in heat transfer increment. The highest values of heat transfer were for *Cu* nanoparticles.

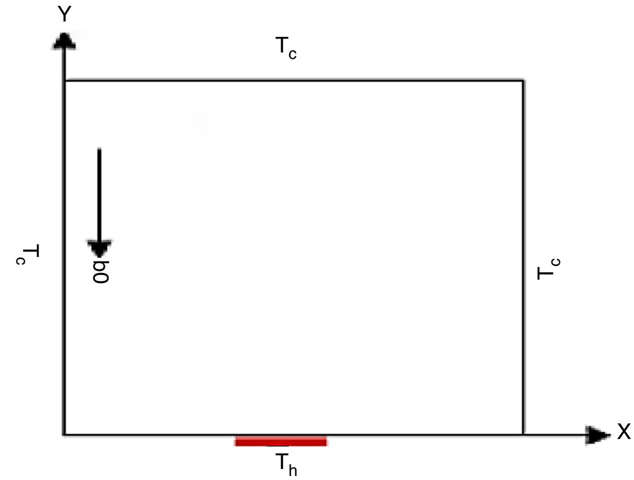


Fig. 4 Physical model of the geometry and boundaries [53]. (Reprinted with the permission of the publisher)

- As increasing the heater size and the type of nanofluid is important in this phenomenon, the discrepancy in heat transfer values is boosted.
- If one changes the aspect ratio, the increment of heat transfer due to the presence of nanoparticles is more noticeable at low aspect ratios.

The other important factor which is considered by researchers to model natural convection of nanofluids in square cavities is heat flux. There are two types of heat flux used in these studies: constant heat flux and variable heat flux. Buyuk Ogut [76] studied natural convection heat transfer in a square enclosure, which was inclined and with heat flux at one side. A polynomial differential quadrature method was considered to be used to solve governing equations. The base fluid was water, and various types of nanoparticles were utilized. The ranges of the parameters were: Ra number between 10^4 and 10^6, the volume fraction of nanoparticle ($0 \leq \varphi \leq 0.2$), and different lengths of the heater. The results demonstrated that while the φ and Ra number increase, the heat transfer significantly increases. On the other hand, Rashidi et al. [77] studied the effects of heterogeneous heat flux on natural convection of Al_2O_3-water nanofluid which was put in a square cavity. This heat flux was at the bottom wall of the cavity, and the overall magnitude of flux was constant but with different profiles. In this regard, they studied 9 different case studies.

All in all, considering different studies done in the literature, one concludes that most of the works by researchers for square enclosures are limited to numerical studies. Just a few studies considered experimental data and a huge gap is in this part which casts doubts on the results of numerical and theoretical studies. Moreover, just a few works considered variable boundary conditions which are more

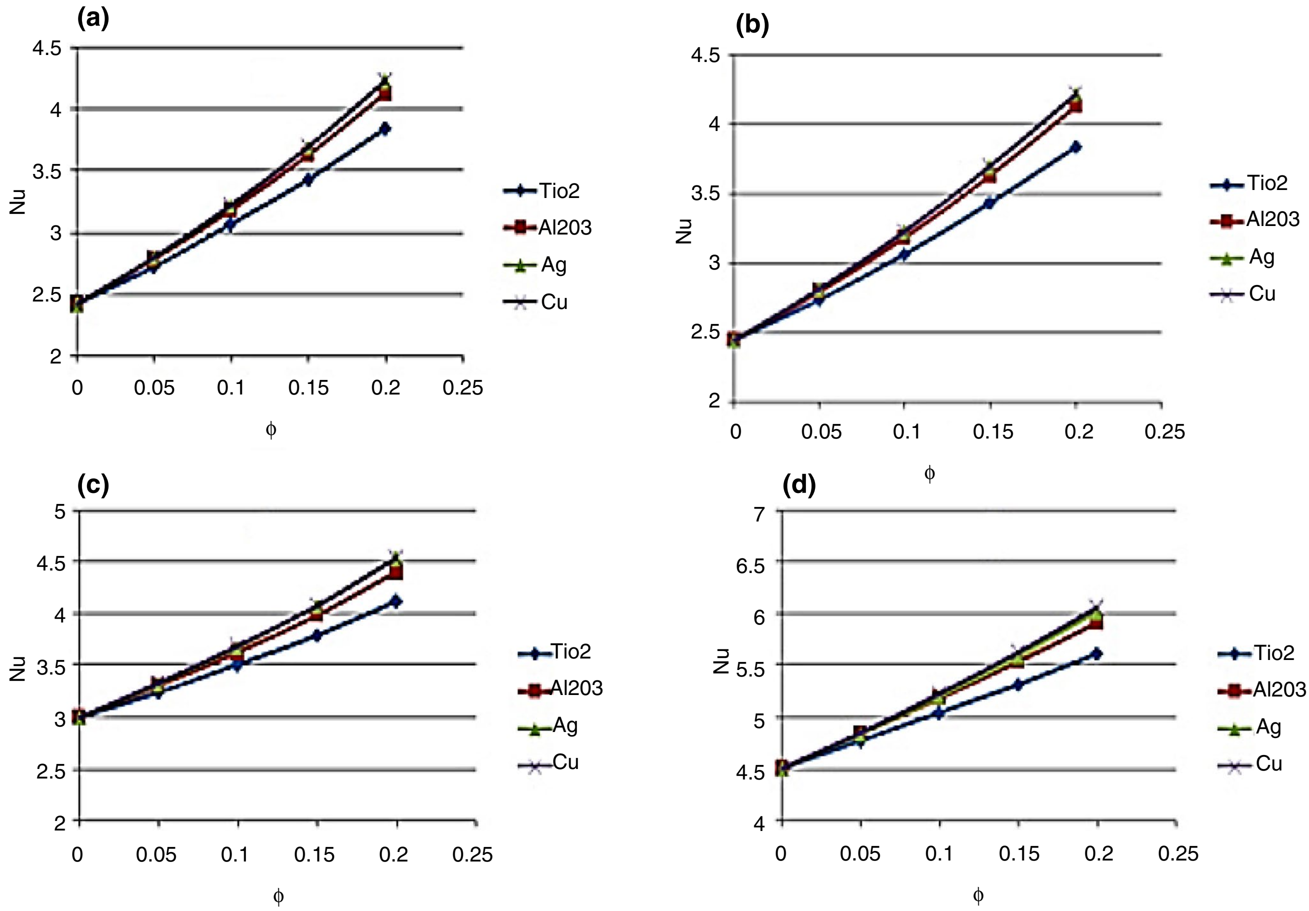


Fig. 5 Variation in average Nu number on the hot wall with various Ra numbers, φ, and nanoparticles [53]. (Reprinted with the permission of the publisher)

realistic and have better results compared to constant boundary conditions. Entropy generation, the effects of heat flux, the effects of radiation, wavy walls, and steady state and transient solves are other important parameters which are studied by researchers.

Circular enclosure

The second widely studied shape of enclosures in natural convection is circular-shaped enclosures. These kinds of enclosures are mostly applicable in solar systems and pipes. Numerous studies and simulations had been done regarding these shapes. There are more experimental studies regarding these enclosures compared to the square cavities. Ali et al. [78] experimentally investigated the natural convection heat transfer of Al_2O_3 nanofluid in a vertical circular enclosure heated from below and for four different concentrations of nanoparticle. Sheikholeslami et al. [45] carried out a numerical study on the natural convection of a magnetic nanofluid in a cylindrical enclosure with a triangular cylinder inside it. The geometry is considered two-dimensional, and the impact of Brownian motion on the quality of thermal conductivity is studied. They examined the influences of Hartmann number (Ha), volume fraction, and Ra number on properties of heat transfer. The studied geometry is presented in Fig. 8. They calculated the influences of Ha and Ra number on the Nu_{ave} over the inner and outer cylinder (Fig. 9). The outcome is that the Nusselt number increases with increasing the Ra number; however, it decreases with increasing the Ha number. There are just a few works done on hybrid nanofluids which are new and applicable in all fields of study. Huminic et al. [79] investigated hybrid nanofluid impact in different cross sections (circular, elliptical, and flat) of a duct flow for different inlet velocities. Their assumptions were: laminar flow, single-phase model, and Newtonian and incompressible hybrid flow. Most of the investigation considered the simple and constant boundary conditions such as insulated and fixed walls, constant heat flux, and constant temperatures; however, Hatami et al. [39] optimized the circular-wavy cavity subjected to a nanofluid. The schematic of the enclosure is shown in Fig. 6. They

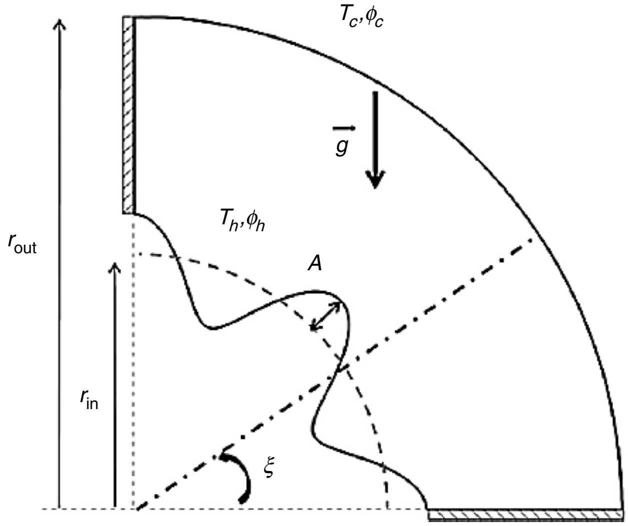


Fig. 6 Schematic view of the cavity with wavy inner wall function [39]. (Reprinted with the permission of the publisher)

solved the governing equations employing a finite element method. The main challenge was the optimization of the shape of the wavy wall to augment the heat transfer. Having discovered the optimum shape of the wavy wall, the impact of fixed coefficients such as Ra number, Le number, and Nr number on isotherm, Nu number, streamlines, and nanoparticle volume fraction was studied. The inner wavy wall function was $r = r_{in} + A\cos(N(\xi))$. Regarding the optimization of the geometry, the Nu number for different A (Amplitude value) and N (Undulation) was calculated, and the results are shown in Fig. 7. The maximum Nusselt number in this figure demonstrates the best heat transfer in the cavity (Figures 8 and 9).

Base fluids rather than water are rarely seen in these enclosures. One of these base fluids is molten salts which are mostly used in dual tanks of concentrating solar power systems. Yu et al. [80] did the numerical and experimental study of molten salt nanofluids in a cylindrical cavity. The cavity was heated at the bottom and released heat at the top and the flow considered to be incompressible Newtonian. There are other considerations such as considering porous media, MHD flows, laminar and transient flow, and variable boundary conditions. Ali et al. [81] analyzed the suspension of nanoencapsulated phase change materials in the porous medium which had a high thermal energy storage and heat transfer compared to conventional nanofluids. Their model was non-equilibrium model which took into account the temperature difference between porous medium and nanoparticles. Al-zamily [40] numerically studied the impact of the magnetic field on natural convection in a semicircular chamber loaded with Cu-H_2O nanofluid using FEM to solve momentum and energy equations. Their main results were that if the Ra number or φ increases, then heat transfer increases, but increasing the Ha number has a negative effect on heat transfer. The effect of the magnetic field is also studied, and accordingly, the results demonstrate that this effect increases if Ra number increases and if the nanoparticle volume fraction decreases.

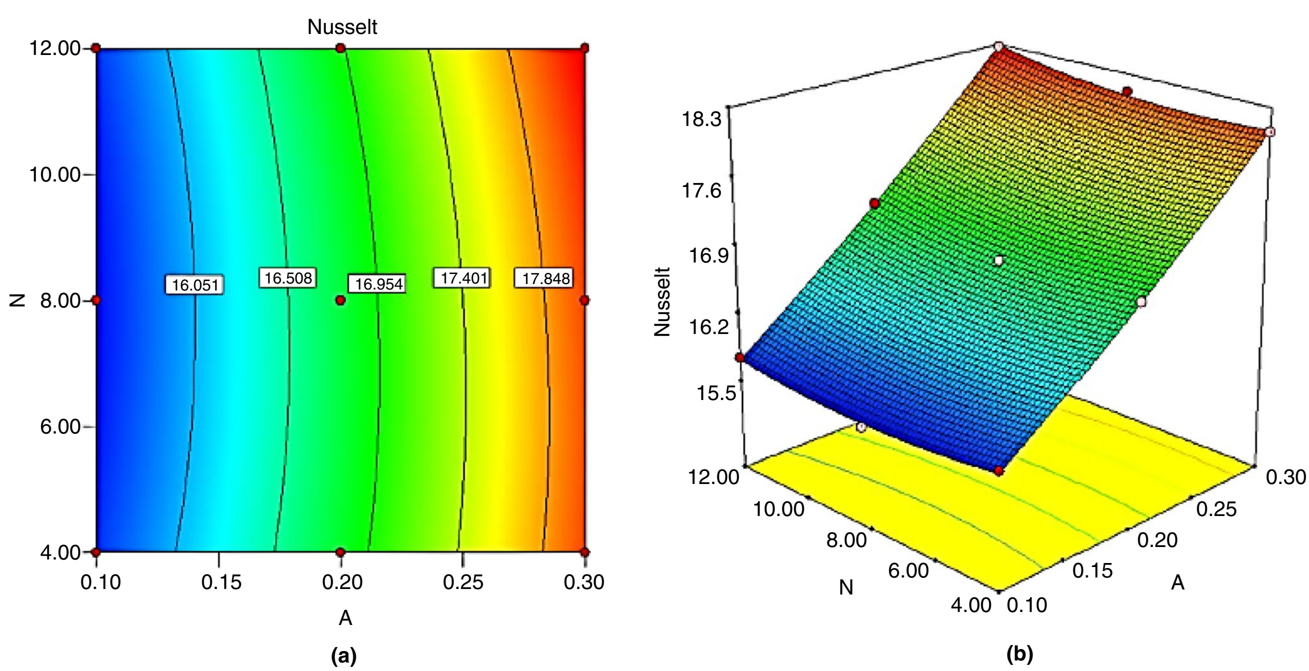


Fig. 7 Effect of A and N parameters on outer wall Nu number **a** 2D and **b** 3D views [39]. (Reprinted with the permission of the publisher)

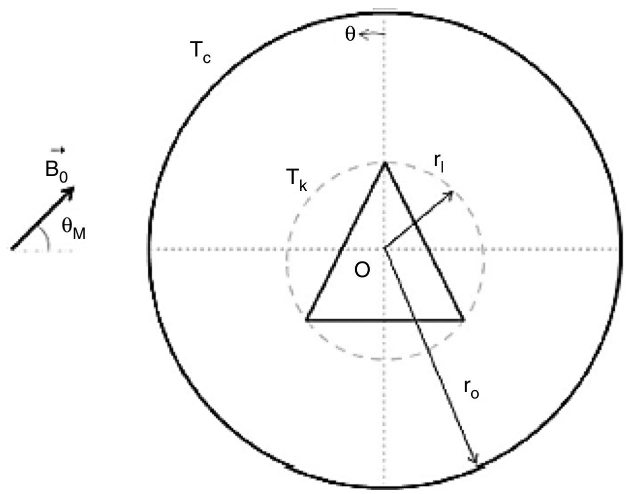


Fig. 8 Geometry of the problem [56]. (Reprinted with the permission of the publisher)

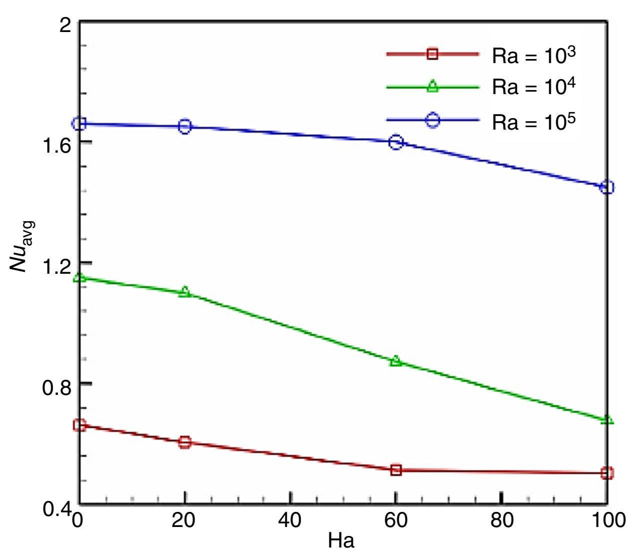


Fig. 9 Effects of Ra and Ha number on average Nu number along the surface of the outer cylinder when $\varphi = 0.04$ [56]. (Reprinted with the permission of the publisher)

To sum up, circular enclosures are mostly interesting to researchers due to their application in different fields of research. Although various parameters such as numerical models, porous media, different nanoparticles, and boundary conditions are considered for these cavities, there is a gap in some parts. As a tangible example, transient flows are rarely solved for these enclosures. Variable boundary conditions which are more precise to predict the realistic data are neglected to be analyzed due to their complexity for these enclosures.

Triangular enclosure

The third popular enclosure shape is triangular. Thermal insulation of buildings, heat exchangers, petroleum reservoirs, panels in electronic devices, conductors, transducers, and industrial equipment are some of the applications of this kind of enclosure. According to the literature, most of the work in this section considers steady-state solve. Aminossadati [82] studied the natural cooling of a right triangular-shaped heat source in a triangular enclosure with the influence of a horizontal magnetic field. The numerical approach was control volume with the help of the SIMPLE algorithm—water–CuO nanofluid utilized as the working fluid, and the power-law scheme used for discretizing the formulations. The ultimate goal was to analyze the effects of φ, Ra number, Ha number, and the coordinates of the heat source on the performance of the heat transfer. Figure 10 shows the schematic of the enclosure shape and the triangular heat source inside it. Figure 11 presents one of the main results. As can be seen, the changes in Nu_{ave} versus the Ha number at different Ra numbers are shown. At low Ra numbers, in which the heat transfer is mostly related to conduction, the average Nu number stays unchanged by variation in the Ha number. For higher Ra numbers (10^5-10^7), where the heat transfer is almost owing to convection, the Nu_m is at a higher rate but decreases by increasing the Ha number since the magnetic field quenches the convection flows. The other important results can be summarized as: the heat transfer of the cavity declines if the heat source is moved away from the cold wall, and an optimum solid volume fraction exists for enhancing heat transfer.

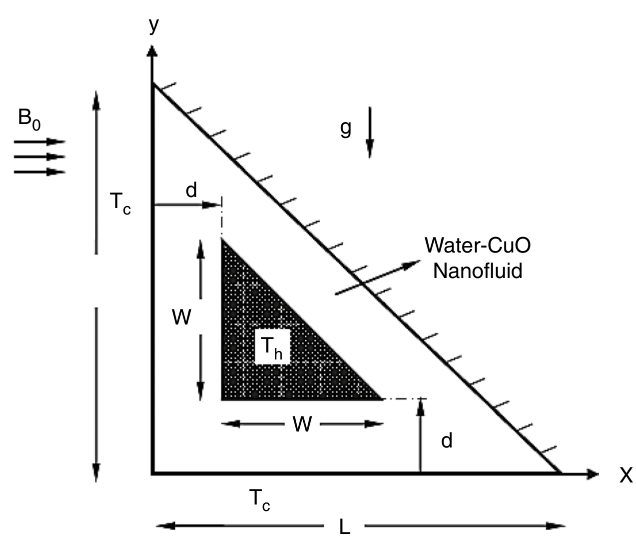


Fig. 10 Schematic view of the physical model [58]. (Reprinted with the permission of the publisher)

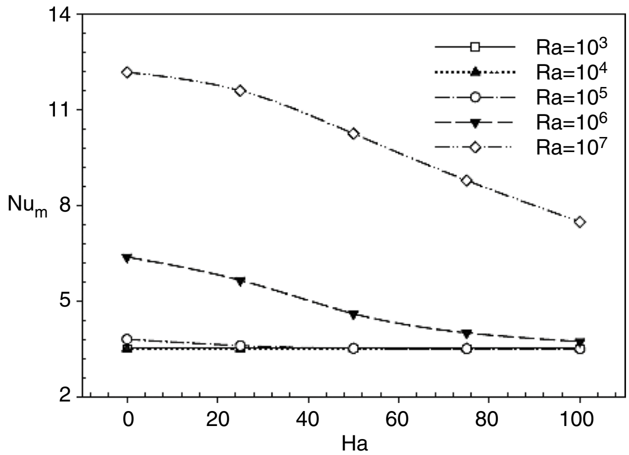


Fig. 11 Variation in the average Nu number with Ha number at different Ra numbers [58]. (Reprinted with the permission of the publisher)

Again just like other types of cavities, there are just few experimental studies for triangular enclosures. Mahian et al. [73] did theoretical and experimental study on natural convection of different enclosures including triangular. They determined density, viscosity, and thermal conductivity of SiO_2-water nanofluid. Constant boundary conditions and walls are widely used in the literature which are not enough applicable in industry and heat transfer process of different components. Selimefendigil et al. [83] performed a numerical study on the MHD natural convection in a triangular enclosure with internal heat generation. They used the FEM of the Galerkin weighted residual to handle the governing equations. The influences of external Ra number (10^4–10^6), internal Ra number (10^4–10^7), flexible wall elastic modulus (500–10^5), Ha number (0–40), and magnetic field inclination angle ($0° - 90°$) on the heat transfer were studied. Some of their results were as follows:

- The average Nu number increases with an external Ra number increase.
- The averaged and local heat transfer decreased by increasing the internal *Ra* number.
- The averaged and local heat transfer decreased as the value of the elastic modulus boosted.
- Heat transfer augments by ascending the value of the magnetic field angle and declines by boosting the values of the magnetic field.

The flow in these enclosures is considered Newtonian, and different methods are used to solve it. Mejri et al. [84] investigated the natural convection in a triangular cavity loaded with water. They used the LBM for solving the coupled equations. The main studied parameters were Ra number (10^3 to 10^6), and the inclination angle $\phi = 0^{\circ}$ to $\phi = 315^{\circ}$. The effects of these two parameters on the streamlines, isotherms, and Nu number were studied. The most important results were:

- Validating the results with previously published papers, it was revealed that the LBM is a suitable method for various engineering problems.
- Heat transfer rate increases whenever the Ra number increases.
- The effect of the angle of inclination on heat transfer increases when the Ra number increases.
- The lower heat transfer rate is achieved at $\phi = 135°$, and the highest heat transfer is achieved at $\phi = 0°$.

Moreover, there are some other factors such as porosity of medium, single-phase and two-phase approaches, the effects of MHD, and entropy generation which are studied in these enclosures. Chowdhury et al. [85] studied the problem of the double-diffusive form of natural convection for Al_2O_3-water nanofluid in a triangular and porous enclosure with heat generation. They tracked the changes of different parameters such as isotherms, streamlines, isoconcentrations, Sherwood number, Nu_{ave}, Ra number, solid volume fraction, heat generation parameter, and Le number. Moreover, some parameters also considered being fixed in their analysis: such as Buoyancy ratio, Prandtl number, and Darcy number. It is concluded that:

- The heat generation plays a pivotal role in the fluid flow pattern and heat and mass transfer.
- The flow strength increases by the rise in the heat generation value and decreasing the value of Le number.
- The Nu_{ave} and Sherwood number ascend by increasing the Ra number.
- If the heat generation increases, then the rate of heat transfer considerably reduces.
- The rate of heat transfer goes up if the solid volume fraction increases, and the rate of mass transfer decreases.

Due to the high applicability of triangular enclosures, it is vital to pay more attention to this type of enclosures. There are few experimental studies in the literature, and the transient solve is rarely seen. The other important factor is variable boundary conditions which are neglected for these enclosures. The base fluid for almost all of these studies is considered water, and there is a huge gap in this section since other base fluids such as oil, molten salt, and ethylene glycol are also in use in industry.

Trapezoidal enclosure

The other shape of the enclosures, which is considered for analyzing heat transfer of nanofluids, is a trapezoid. This type of enclosure is applicable in different fields like solar collectors and packed bed reactors. Majority of work done on this enclosure assumes numerical, laminar, and steady two-dimensional flow. Saleh et al. [35] modeled transport equations by stream vorticity formulation for enhancement of heat transfer of a nanofluid in a trapezoidal enclosure. The finite difference approach is applied to tackle the governing equations. Figure 12 shows a schematic of the geometry. The influences of Grashof number (Gr), the volume fraction of nanoparticles, and the inclination angle of the sloping wall on temperature patterns and heat transfer are presented within the enclosure. The main idea of this study was to develop a new correlation for the Nu_{ave} as a function of the sloping wall's angle. Once the temperature and the conductive heat transfer coefficient of the base fluid and nanofluid are known, the Nu_{ave} is calculated by integrating over the sloping wall. They used two different nanoparticles, and the outcome of the average Nu number with volume fraction is presented in Fig. 13. They also studied the heat transfer for some angles of the sloping wall, the effect of the Gr number on the Nu number, and the impact of solid volume fraction. The main results of their study can be aggregated together as follows:

- The frame of the fluid flow inside the enclosure depends on the wall inclination angle, the concentration and type of nanoparticle, and the Gr number.
- The most fruitful procedure to enhance the heat transfer in the cavity mentioned above is when the Cu nanoparticles with high φ combined with a sharp sloping wall.

Moreover, porous medium and constant boundary conditions are also widely studied. Sheremet et al. [86] perused

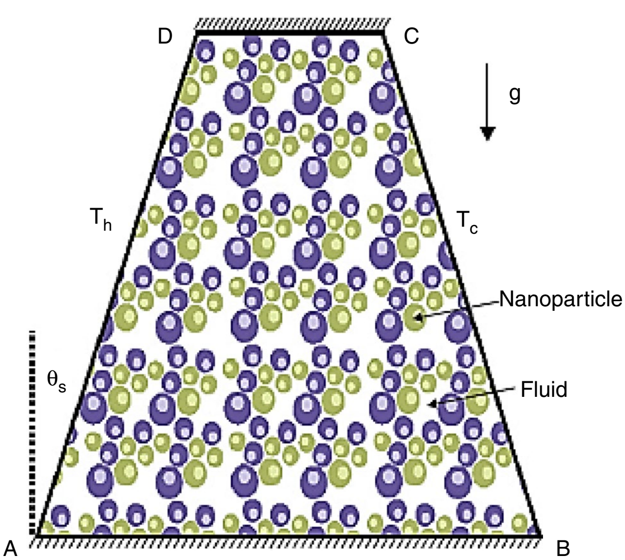


Fig. 12 Schematic representation of the model [35]. (Reprinted with the permission of the publisher)

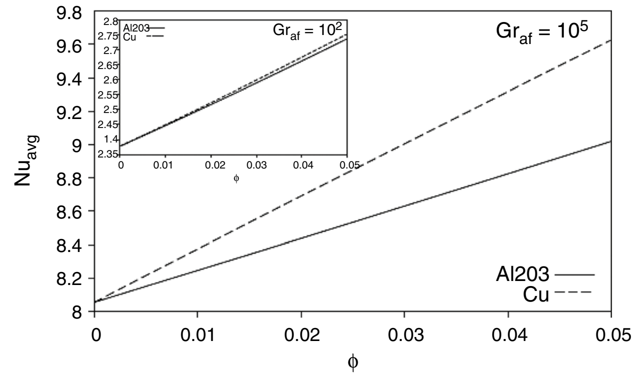


Fig. 13 Plots of average Nu number versus φ for two types of nanoparticles [35]. (Reprinted with the permission of the publisher)

the steady-state mode of free convection inside the right-angle and porous trapezoidal enclosure, which was loaded by a nanofluid. They analyzed the flow for different governing parameters (Nb, Nt, Nr, Le, A) and the range of a Ra number ($50 \leq Ra \leq 1000$) using finite difference method. Their ultimate goal was to predict the coordinates of minimum heat transfer in the trapezoidal cavity. The model which was proposed by Buongiorno [49] was intertwined with Darcy law for the porous medium and also Boussinesq approximation for convective forces. They concluded that the Sherwood and Nu numbers and also flow strength were ascending functions of Ra number and descending functions of Le number and aspect ratio. On the other hand, there is a limited research on transient, unsteady, and non-Newtonian with variable boundary conditions. Alsabery et al. [87] studied transient natural convection of a non-Newtonian nanofluid which had sinusoidal boundary conditions, and they did so with finite element method. They chose Ag, Cu, Al_2O_3, and TiO_2 were the nanoparticles which were used for investigation. They demonstrated that the effect of variable temperature at the side wall is on phase deviation of fluid. Some others considered the thermal conductivity and viscosity as variable parameters and considered the buoyancy-driven heat transfer. Roslan et al. [88] studied the natural convection inside a trapezoidal enclosure with variable viscosity and thermal conductivity. They modeled transport equations by vorticity stream formulation and used FEM to discreet the governing equation. They studied the influences of the Ra number, volume fraction, base angle, and size of nanoparticle on heat transfer. Their results lead to the following conclusions:

- Convective heat transfer depends on volume fraction, Ra number, the base angle, and the size of the nanoparticle. The role of the viscosity is higher than thermal conductivity in heat transfer performance.
- The trapezoidal shape has a better performance of heat transfer than the square shapes.

The effect of magnetic field which can be constant, or variable is another factor that is considered in these types of enclosures. Miroshnichenko et al. [89] studied the natural convection in a partially open trapezoidal cavity with the effect of a uniform magnetic field and a CuO nanofluid. The boundary conditions are defined in the way that horizontal walls are assumed to be adiabatic, the inclined wall is heated, and cold nanoliquid goes into the enclosure from an open boundary. They used the finite difference method to explore the influences of inclination angle and magnetic field intensity with φ. The analysis is done in the limit of governing parameters such as Ra number (10^3–10^5), Ha number (0, 10, 50, 100), Pr number (7.0), the inclination angle of the magnetic field ($\alpha = 0$–π), and nanoparticle volume fraction ($0 \le \varphi \le 0.04$). They developed an in-house CFD code with C++ programming and validated their work by the works of other authors. Some of their results are summarized here:

- An increment in Ha number results in suppressing the flow rate and heat transfer.
- If the magnetic field and gravity force are parallel, then a considerable decline of flow and heat transfer will be experienced.
- Growth in the Ha number causes a widening of α.

To sum up, although trapezoidal enclosures are so common in different engineering and medial processes, they are not widely studied compared to other types of enclosures. The most important factor that should be studied about these enclosures is boundary layer analysis and turbulent flow which is not done yet according to literature review of this paper. Other parameters such as porous medium, single- and two-phase approach, steady and transient flow, and the effect of MHD are studied but yet need to be more analyzed. On the other hand, the lack of experimental data in these enclosures is also felt.

Unconventional shapes

Recently, unconventional shapes are of interest in order to enhance heat transfer compared to traditional simple shapes and regular enclosures. Making wavy walls and variation in geometries like bending the walls or assuming sinusoidal walls are some examples of these unconventional shapes. Sheremet et al. [86] did the numerical study of magnetic natural convection inside a wavy open porous enclosure loaded with a Cu-H_2O nanofluid. The considered boundary conditions were heating from the right bottom corner, cooling from the left wavy wall, and the adiabatic bottom wall. Figure 14 demonstrates a schematics view of the enclosure. One of the most important results was the impact of the inclination angle of the magnetic field on the heat transfer of the cavity. They studied the effect of this angle on

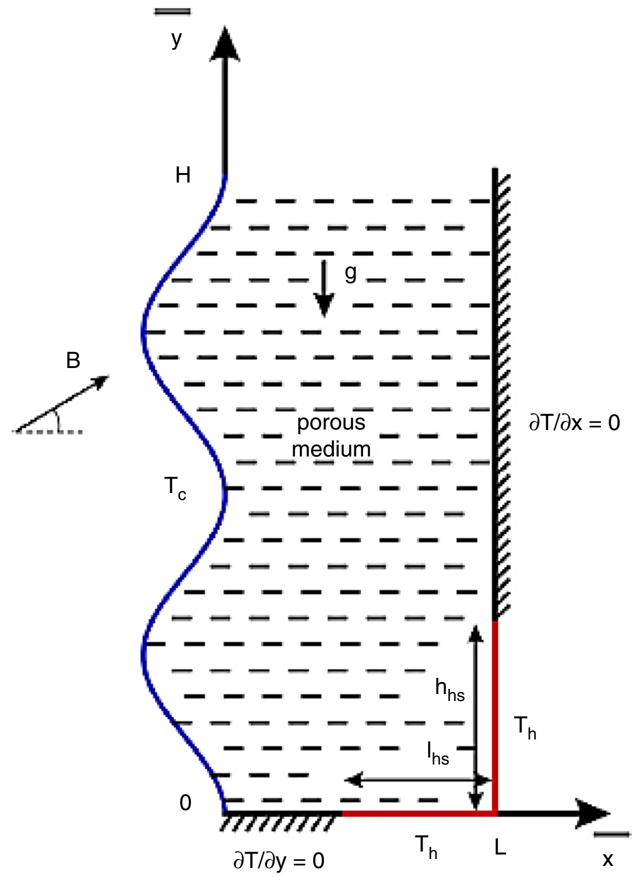


Fig. 14 Physical model and coordinate system [64]. (Reprinted with the permission of the publisher)

streamlines and isotherms for the constant values of Ha number, Ra number, and φ. This is shown in Fig. 15. It is concluded that if the inclination angle (γ) increases from 0 to $\pi/2$, then the convective flow and composition of recirculation inside the cavity intensify. Some of the main findings are listed as:

- The effect of φ and γ on the heat transfer rate is non-uniform.
- Growth in Ha number causes convective flow rate to reduce and also leads to the establishment of circulation close to the bottom wall.
- An increment in the γ causes Lorentz force to ascend, which suppresses the buoyancy force.

Since these geometries are movable, some research is done to find the optimum location and shape of the cavities and shapes used inside them. Hatami and Safari [90] performed the natural convection of nanofluid inside a wavy wall cavity, which is shown in Fig. 16, while a heated cylinder is placed within the enclosure and solved the equations by the finite element method. In their work, the cylinder

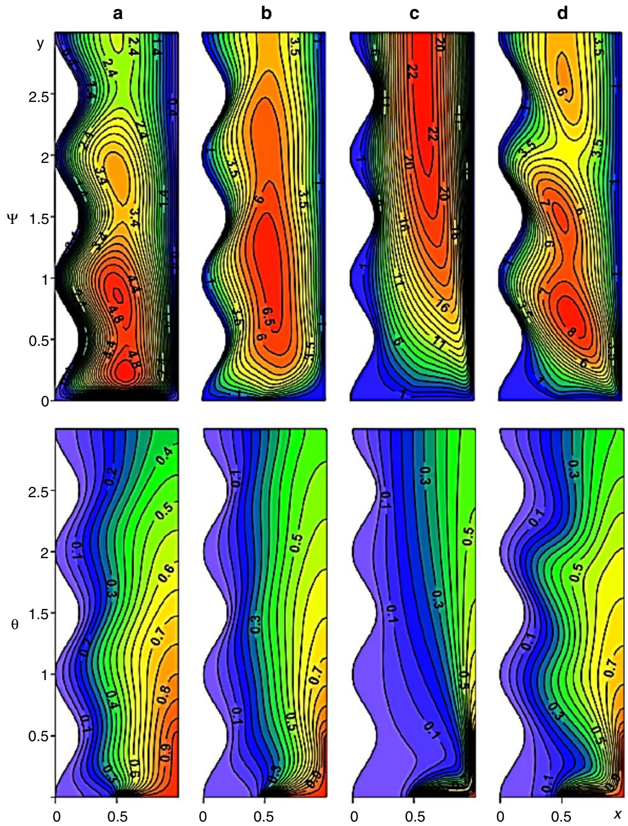


Fig. 15 Streamlines and isotherms for Ra = 500, Ha = 10, $\phi = 0.02$: $\gamma = 0 - a, \gamma = \pi/4 - b, \gamma = \pi/2 - c, \gamma = 3\pi/4 - d$ [64]. (Reprinted with the permission of the publisher)

is movable in Y and X directions, which influences the nanoparticle concentration, streamlines, and temperature contours. Regarding finding the best position of the heated

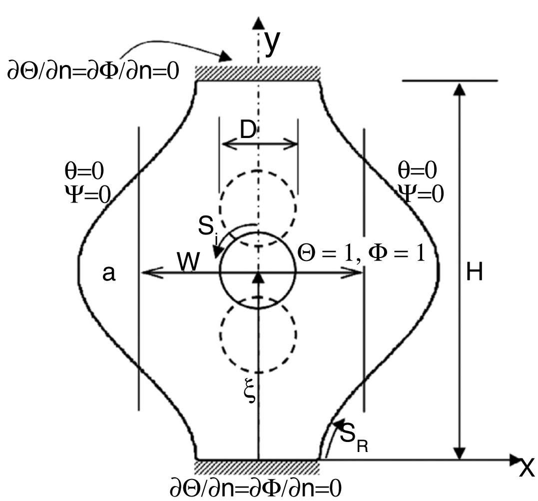


Fig. 16 Enclosure geometry and boundary conditions [65]. (Reprinted with the permission of the publisher)

cylinder within the enclosure, various geometries have been sketched and perused. It is clear that virtually in all boundaries, the center position of the cylinder (Yc = Xc = 0) causes to higher Nu_{ave}. Figure 17 demonstrates the results of the local Nu number.

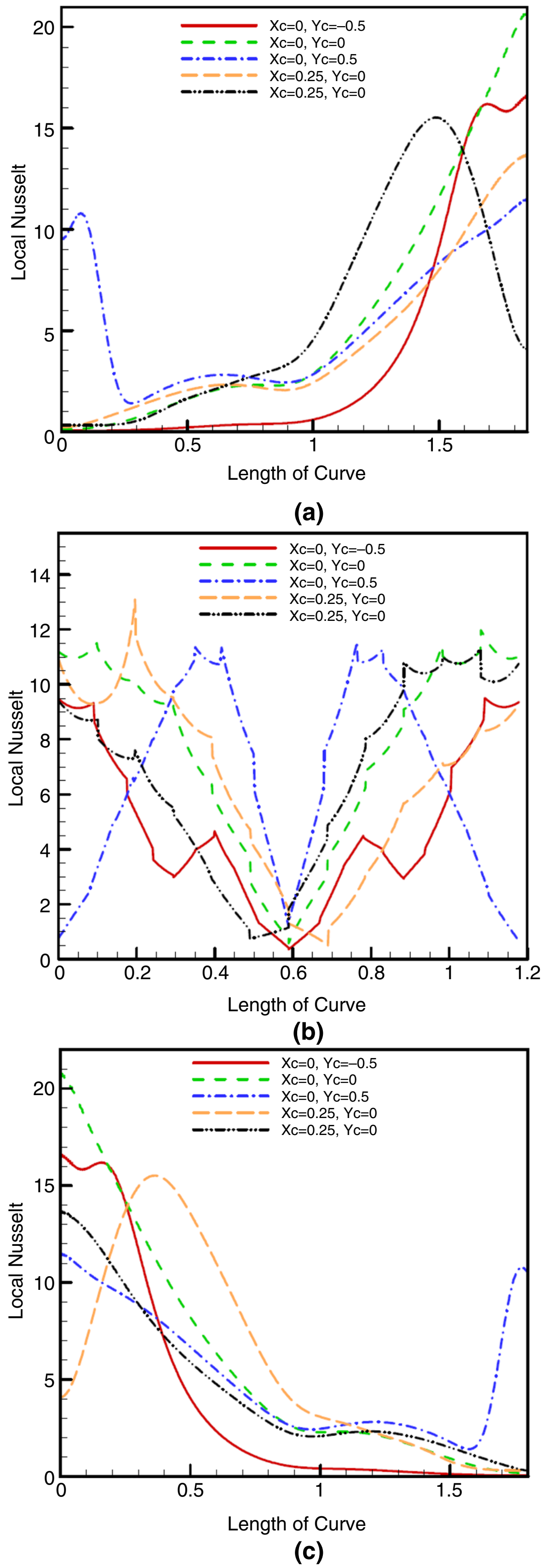
Another interesting tool to control and enhance heat transfer in these cavities is baffles which have myriad of applications in industry. Abedini et al. [91] perused magnetic free convection of water-Fe_3O_4 nanofluid inside a C-shaped baffled cavity. They subjected the enclosure to a magnetic field, and the temperature of the vertical wall on the left side was the constant hot temperature, the right one was the constant cold temperature, and the other walls were adiabatic. Figure 18 shows the boundaries and geometry. They had the following assumptions to solve the natural convection in the enclosure:

- Viscous dissipation, energy storage, and generation have been ignored.
- There is thermal equilibrium among the solid particles and the pure fluid.
- The nanofluid considered a Newtonian fluid.

In order to model the geometry, they used FORTRAN code and discretized the equations with the finite difference method. They did the parametric study on the effects of parameters such as Ra number, aspect ratio, magnetic field, φ, baffle length on the isotherms, streamlines, Nu_{loc}., and Nu_{ave}. Their main conclusions were:

- The Nu number increases by boosting the enclosure aspect ratio.
- If the φ goes up, the cooling of the cavity can be improved.
- If the enclosure aspect ratio goes higher, the impact of nanoparticles on the Nu number becomes more pronounced.
- At the lowest part of the hot wall, the utmost impact of the baffle on the heat transfer occurs.
- In general, ascending the baffle length causes heat transfer to boost.

Entropy generation, the effects of magnetic field, single- and two-phase approaches, and porosity are the other important parameters which are considered in these cavities. Cho et al. [92] analyzed entropy generation and natural convection in a wavy enclosure with the water-based nanofluid. The schematic view of the enclosure is shown in Fig. 19. They considered the left wall of the enclosure to be heated by a fixed heat flux and the right one to be maintained at a fixed low temperature and other walls to be adiabatic. They used three various nanofluids (Al_2O_3–H_2O, Cu–H_2O, and TiO_2–H_2O), and the ultimate goal was to enhance the natural



◀ **Fig. 17** Local Nusselt number for **a** left wall, **b** inside the cylinder wall, and **c** right wall [65]. (Reprinted with the permission of the publisher)

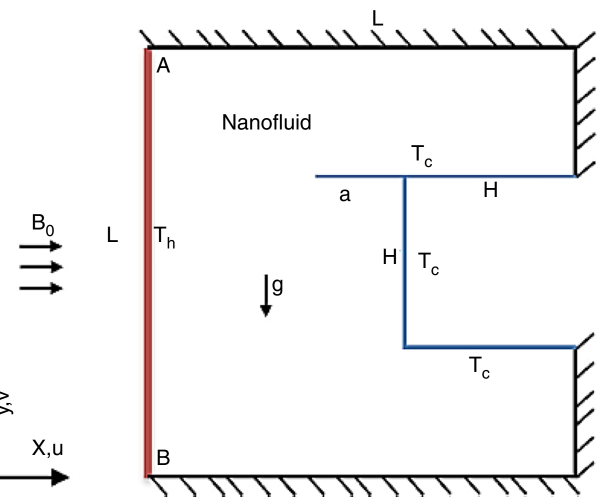


Fig. 18 C-shaped enclosure with baffle subjected to the magnetic field [66]. (Reprinted with the permission of the publisher)

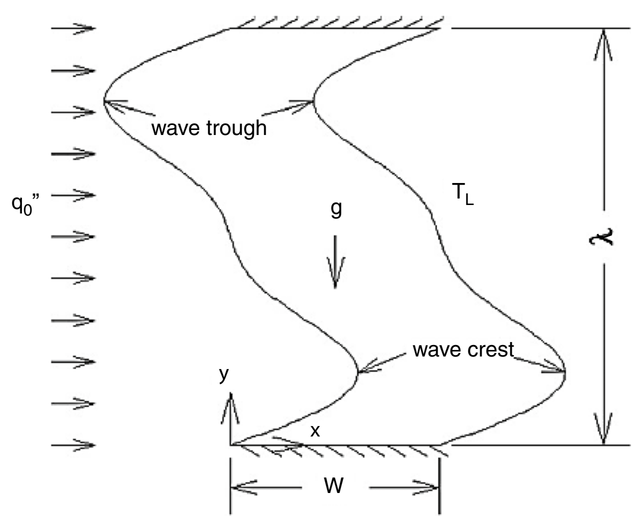


Fig. 19 Schematic illustration of wavy wall enclosure [67]. (Reprinted with the permission of the publisher)

convection heat transfer and reducing the entropy generation. Parvin et al. [93] reported the influence of the magnetic field on natural convection flow in a prism-shaped enclosure loaded with nanofluid. They applied the magnetic field normal to the sidewalls and FEM of the Galerkin weighted residual scheme to solve the transport equations. The shape of the enclosure with the boundary conditions is shown in Fig. 20. Their results demonstrate that the local Nu number

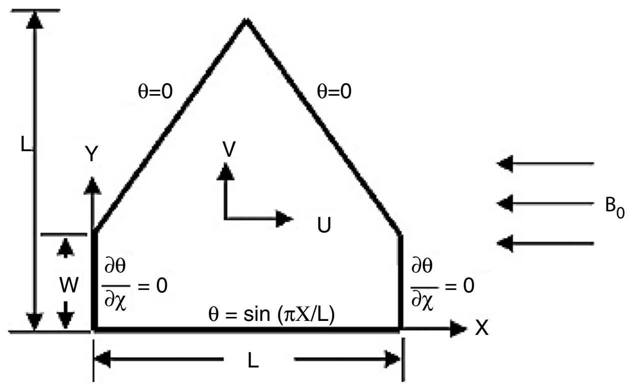


Fig. 20 Schematic view of the physical system [68]. (Reprinted with the permission of the publisher)

sharply decreases for higher Ha numbers. Figure 21 shows their results. A similar trend of heat transfer is seen for both the base fluid and the nanofluid, while the nanofluid has a higher heat transfer rate. The major outcomes of their study are the following:

- Increasing the Ha number reduces the velocity.
- Increasing the magnetic field results in increasing the fluid temperature.
- Rising Ha number decreases the heat flow.

Unconventional enclosures are becoming the most popular cavities among researchers. Not only do they are more applicable in new fields of engineering compared to common enclosures such as square and circle, but also it is possible for researcher to change the shape and optimize these cavities to reach the best heat transfer. Although some work is done working on these types of enclosures, there are a lot of unknown parts such as turbulent flow and the effects of boundary layer behavior, optimization tools for finding the best geometries, transient solves, and more experimental data.

Table 1 demonstrates all the significant published works done in the natural convection field of study in enclosures.

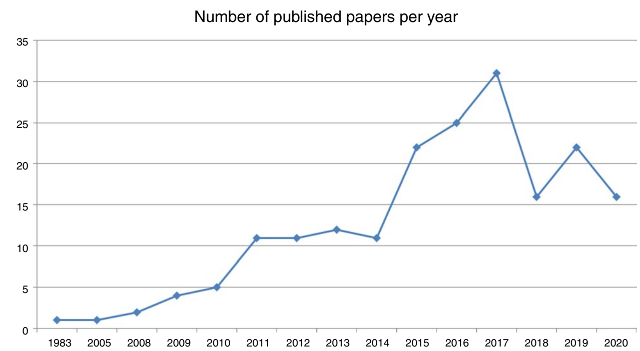


Fig. 22 Trend of published papers during the last decades

There are about 197 published works in this field. The flow regime in all of these studies is laminar, and the base fluid is almost water: in some cases, CMC, Kerosene, ethylene Glycol, oil, and air. Various parameters such as geometry, dimensions, Ra number, Gr number, nanoparticle shape, concentration and size, the enhancement of heat transfer, and the schematics of enclosures are also shown in this table.

Statistical analysis

This section is allocated to the statistical analysis of the natural convection in enclosures. Figure 22 demonstrates the trend of the published literature over the last decade. Figure 23 shows the percentage of contribution of each nanoparticle in natural convection studies. According to data, Al_2O_3 and Cu constitute 34% and 27% of the total of this subject, respectively, and are the most frequent nanoparticles used in nanofluids natural convection in cavities. It seems that their thermophysical properties in analytical and experimental results of various studies are the main factors for utilizing these nanoparticles. The third-largest segment is TiO_2, with 12% followed by Ag and then others. Furthermore, SiO_2, as well as Au, contributes the same rate to nanoparticles with 1%.

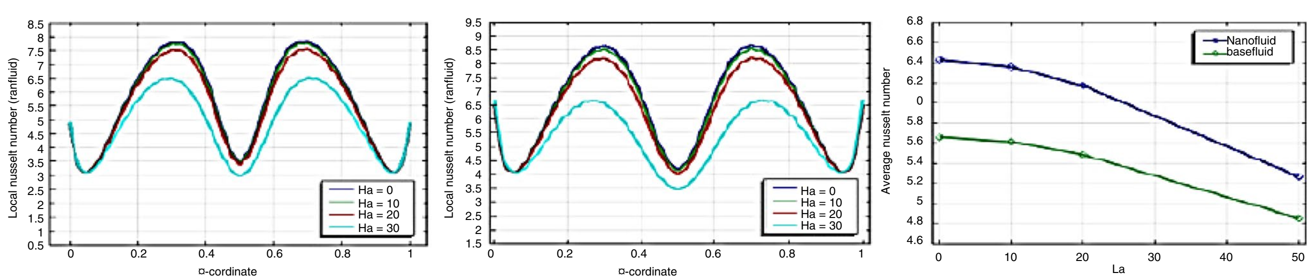


Fig. 21 Effect of Hartmann number on local and average Nusselt number for base and nanofluid [Ra = 10^5, Prandtl number, Pr = 6.2, Al_2O_3 nanofluid with volume fraction 5% [68]. (Reprinted with the permission of the publisher)

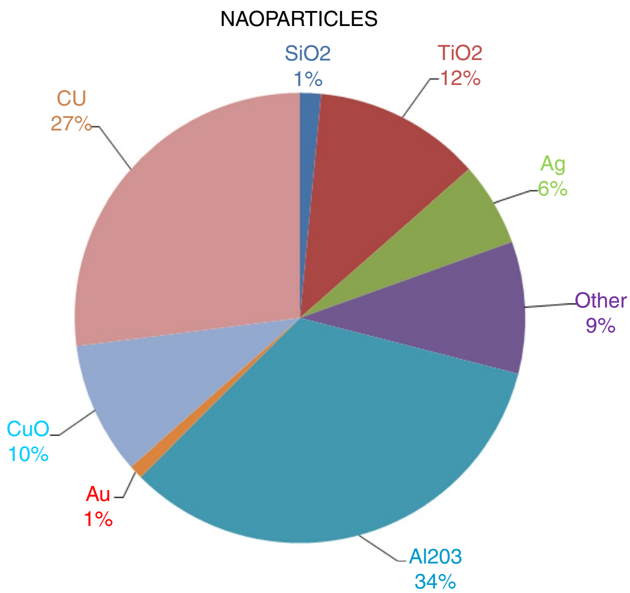


Fig. 23 Most frequent nanoparticles

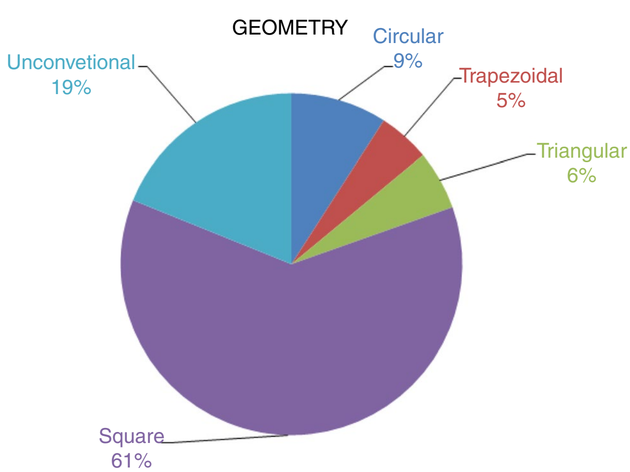


Fig. 24 Most frequent shapes of the enclosure

The pie chart of the cavity geometries in natural convection is illustrated in Fig. 24. Square geometry contributes to the most significant rate to the geometry subject with 61%, while trapezoidal accounts for a mere 5% of the total. The percentage of unconventional geometries is 19%, and circular and triangular make up 9% and 6%, respectively. This figure reveals that most of the authors are interested in square and then unconventional cavities.

Future works

Natural convection heat transfer is reviewed for different enclosures, and various parameters are considered by researchers in order to model and investigate the flow behavior. They did many numerical simulations in which the boundary conditions are constant and flow is laminar and in steady-state mode. If one considers the water wall which is used to mitigate the extreme of heating and cooling in buildings, the heat transfer behavior of the water wall is periodic since the thermal forcing on this wall is changing during day and night. Moreover, the transfer of heat into and out of water is due to natural convection boundary layer (NCBL) [94]. There are three stages of evolution in flow field; start-up stage, transition stage, and fully developed steady stage [95]. The steady state is mostly studied, and there is no gap to be felt in this part. On the other hand, transient stage is just recently investigated by researchers and future work should be allocated to this part. Moreover, start-up stage is another important stage which affects the boundary layer flow behavior if the wall is infinite or this stage has perturbations at the beginning of flow formation. This stage is not studied yet in enclosures. If one wants to investigate the transition stage, he should take into account three time characteristics: forcing period, development time of the boundary layer, and filling time of the cavity [94].

Furthermore, the lack of experimental investigations is felt in this review. If one wants to rely on the outputs of the investigations of natural convection in cavities, he should be able to compare these results by experimental data. Due to lack of equipment and difficulties of making test stands for analyzing numerical data, this goal is not achieved yet. Most of the assumptions made in this field of study are based on constant boundary conditions which are not realistic, and it is likely to have noticeable errors compared to experimental data. Non-Newtonian and compressible flows are types of flows which are not enough studied, and future work would consider these flows and focus on them more than before.

Ultimately, future geometries will be unconventional and variable. Blood cells, geometries with elastic walls, new solar collectors, food industry, heat exchangers, fuel cells, and micro-electronic equipment are examples of complex geometries. The literature demonstrates that these enclosures are not investigated broadly and there is an urgent need to focus on these types of enclosures which are helpful to ameliorate heat transfer performance of nanofluids.

Conclusions

Some of the noticeable conclusions from this literature review can be summarized as follows:

- The generation of thermal entropy increases by an increase in the porosity of medium due to higher friction in a fluid.
- The average Nu number has an increasing trend by increasing the Ra number and decreasing the Ha number, while the other parameters are constant.
- Nu number and the Ra number increase by increasing the nanoparticle volume fraction, but the Ha number decreases.
- At low Ra numbers, conduction heat transfer is the pivotal factor, while at high Ra numbers, the buoyancy-induced convection heat transfer becomes dominant.
- The performance of the trapezoidal shape is better than the square shape in the enhancement of heat transfer.
- Heat transfer declines with increasing the volume fraction of nanoscale ferromagnetic for diverse Ra numbers.
- The method of Lattice Boltzmann based on double population is valid and robust in the simulation of natural convection with nanofluid in geometries with curved boundaries.
- The vertical and horizontal magnetic fields increase the effect of heat conduction.
- If one makes the magnetic field more powerful, it reduces convection heat transfer and, consequently, the conduction heat transfer part becomes prevail.
- The rectangular shape is the dominant type of cavity utilized in natural convection research, and Al_2O_3, Cu, and TiO_2 are the most common nanoparticles in this specific field of study.
- Natural convection in cavities is a new field of research that has the capacity of a significant amount of study to better understanding the thermophysical characteristics of the phenomena.

References

1. Sheremet MA. Steady-state free convection in right-angle porous trapezoidal cavity filled by a nanofluid: Buongiorno's mathematical model. Eur J Mech B/Fluids. 2015;53:241–50.
2. A. Asadi. A guideline towards easing the decision-making process in selecting an effective nanofluid as a heat transfer fluid. Energy Convers Manage. 2018: 175.
3. Asadi A. An experimental and theoretical investigation on heat transfer capability of Mg (OH) 2/MWCNT-engine oil hybrid nano-lubricant adopted as a coolant and lubricant fluid. Appl Therm Eng. 2018;129:577–86.
4. Masuda H, Ebata K, Teramae K. Alteration of thermal conductivity and viscosity of liquid by dispersing ultra-fine particles (dispersion of γ-Al2O3, SiO2 and TiO2 ultra-fine particles). Netsu Bussei. 1993;7:227–33.
5. Maxwell J. Electricity and magnetism. Oxford: Clarendon Press; 1873.
6. Asadi A, Ibrahim MA, Loke KF. An experimental study on characterization, stability and dynamic viscosity of CuO-TiO2/water hybrid nanofluid. J Mol Liq. 2020;307:112987.
7. Alarifi IM, Alkouh AB, Ali V, Nguyen HM, Asadi A. On the rheological properties of MWCNT-TiO2/oil hybrid nanofluid: an experimental investigation on the effects of shear rate, temperature, and solid concentration of nanoparticles. Powder Technol. 2019;355:157–62.
8. Asadi A, Pourfattah F. Heat transfer performance of two oil-based nanofluids containing ZnO and MgO nanoparticles; a comparative experimental investigation. Powder Technol. 2019;343:296–308.
9. Asadi A, Ibrahim MA, Loke KF. An experimental investigation on the effects of ultrasonication time on stability and thermal conductivity of MWCNT-water nanofluid: finding the optimum ultrasonication time. Ultrason Sonochem. 2019;58:104639.
10. Asadi A, Asadi M, Siahmargoi M, Asadi T, Andarati M. G The effect of surfactant and sonication time on the stability and thermal conductivity of water-based nanofluid containing Mg(OH)2 nanoparticles: an experimental investigation. Int J Heat Mass Transf. 2017;108:191–8.
11. Esfe MH. Thermal conductivity of Cu/TiO2-water/EG hybrid nanofluid: experimental data and modeling using artificial neural network and correlation. Int Commun Heat Mass Transfer. 2015;66:100–4.
12. Alshayji A, Asadi A, Alarifi IM. On the heat transfer effectiveness and pumping power assessment of a diamond-water nanofluid based on thermophysical properties: an experimental study. Powder Technol. 2020;373:397–410.
13. Esfe MH, Firouzi M, Afrand M. Heat transfer efficiency of Al 2 O 3 -MWCNT/thermal oil hybrid nanofluid as a cooling fluid in thermal and energy management applications: an experimental and theoretical investigation. Int J Heat Mass Transf. 2018;117:474–86.
14. Alshayji A, Asadi A, Alarifi IM. Effects of magnetic field on the convective heat transfer rate and entropy generation of a nanofluid in an inclined square cavity equipped with a conductor fin: considering the radiation effect. Int J Heat Mass Transf. 2019;133:256–67.
15. Asadi A, Bakhtiyari AN, Alarifi IM. Predictability evaluation of support vector regression methods for thermophysical properties, heat transfer performance, and pumping power estimation of MWCNT/ZnO–engine oil hybrid nanofluid. Eng Comput. 2020: 1–11.
16. Asadi A, Bakhtiyari AN, Alarifi IM. Feasibility of least-square support vector machine in predicting the effects of shear rate on the rheological properties and pumping power of MWCNT–MgO/oil hybrid nanofluid based on experimental data. J Therm Anal Calorim. 2020.
17. Alarifi IM, Nguyen HM, Naderi Bakhtiyari A, Asadi A. Feasibility of ANFIS-PSO and ANFIS-GA models in predicting thermophysical properties of Al2O3-MWCNT/Oil hybrid nanofluid,||. Materials. 2019;12:21.
18. Pourfattah F, Sabzpooshani M, Bayer Ö, Toghraie D, Asadi A. On the optimization of a vertical twisted tape arrangement in a channel subjected to MWCNT–water nanofluid by coupling numerical simulation and genetic algorithm. J Therm Anal Calorim. 2020: 1–13.

19. Lyu Z, Pourfattah F, Arani AAA, Asadi A, Foong LK. On the thermal performance of a fractal microchannel subjected to water and kerosene carbon nanotube nanofluid. Sci Rep. 2020;10(1):1–16.
20. Lyu Z, Pourfattah F, Arani AAA, Asadi A, Foong LK. Thermal and fluid dynamics performance of MWCNT-water nanofluid based on thermophysical properties: an experimental and theoretical study. Sci Rep. 2020;10(1):5185.
21. Asadi A, et al. Recent advances in preparation methods and thermophysical properties of oil-based nanofluids: a state-of-the-art review. Powder Technol. 2019;352:209–26.
22. Asadi A, et al. Effect of sonication characteristics on stability, thermophysical properties, and heat transfer of nanofluids: a comprehensive review. Ultrason Sonochem. 2019;58:104701.
23. Arshad A, Jabbal M, Yan Y, Reay D. A review on graphene based nanofluids: preparation, characterization and applications. J Mol Liq. 2019;279:444–84.
24. Khanafer K, Vafai K, Lightstone M. Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids. Int J Heat Mass Transf. 2003;46(19):3639–53.
25. Asadi A, et al. The effect of temperature and solid concentration on dynamic viscosity of MWCNT/MgO (20–80)–SAE50 hybrid nano-lubricant and proposing a new correlation: an experimental study. Int Commun Heat Mass Transfer. 2016;78:48–53.
26. Asadi M, Asadi A. Dynamic viscosity of MWCNT/ZnO-engine oil hybrid nanofluid: an experimental investigation and new correlation in different temperatures and solid concentrations. Int Commun Heat Mass Transf. 2016: 76.
27. Choi SU, Eastman JA. Enhancing thermal conductivity of fluids with nanoparticles. 1995.
28. Dahani Y, Hasnaoui M, Amahmid A, Hasnaoui S. Lattice-Boltzmann modeling of forced convection in a lid-driven square cavity filled with a nanofluid and containing a horizontal thin heater. Energy Procedia. 2017;139:134–9.
29. Esmaeili H, Armaghani T, Abedini A, Pop I. Turbulent combined forced and natural convection of nanofluid in a 3D rectangular channel using two-phase model approach. J Therm Anal Calorim. 2019;135(6):3247–57.
30. Chen CL, Chang SC, Chang CK. Lattice Boltzmann simulation for mixed convection of nanofluids in a square enclosure. Appl Math Model. 2015;39:2436–51.
31. Sheikholeslami M, Gorji-Bandpy M, Ganji DD, Rana P, Soleimani S. Magnetohydrodynamic free convection of Al2O3-water nanofluid considering Thermophoresis and Brownian motion effects. Comput Fluids. 2014;94:147–60.
32. Hoseinpour B, Ashorynejad HR, Javaherdeh K. Entropy generation of nanofluid in a porous cavity by lattice boltzmann method. J Thermophys Heat Transfer. 2017;31(1):20–7.
33. Mamun MAH, Tanim TR, Rahman MM, Saidur R, Nagata S. Analysis of mixed convection in a lid driven trapezoidal cavity. [S.l.]: [s.n.], 2011.
34. Saha SC. Scaling of free convection heat transfer in a triangular cavity for Pr > 1. Energy Build. 2011;43(10):2908–17.
35. Saleh H. Natural convection heat transfer in a nanofluid-filled trapezoidal enclosure. Int J Heat Mass Transf. 2011;54(1–3):194–201.
36. Sun Q, Pop I. Free convection in a triangle cavity filled with a porous medium saturated with nanofluids with flush mounted heater on the wall. Int J Therm Sci. 2011;50(11):2141–53.
37. Mliki B, Abbassi MA, Omri A, Zeghmati B. Augmentation of natural convective heat transfer in linearly heated cavity by utilizing nanofluids in the presence of magnetic field and uniform heat generation/absorption. Powder Technol. 2015;284:312–25.
38. Saeid NH, Mohamad AA. Natural convection in a porous cavity with spatial sidewall temperature variation. Int J Numer Meth Heat Fluid Flow. 2005;15(6):555–66.
39. Hatami M, Song D, Jing D. Optimization of a circular-wavy cavity filled by nanofluid under the natural convection heat transfer condition. Int J Heat Mass Transf. 2016;98:758–67.
40. Al-Zamily AMJ. Effect of magnetic field on natural convection in a nanofluid-filled semi-circular enclosure with heat flux source. Comput Fluids. 2014;103:71–85.
41. Chang C. Hydromagnetic flow with thermal radiation. Convect Conduct Heat Transf 2011.
42. Nemati H, Farhadi M, Sedighi K, Ashorynejad HR, Fattahi EJSI. Magnetic field effects on natural convection flow of nanofluid in a rectangular cavity using the Lattice Boltzmann model. Scientia Iranica. 2012;19(2):303–10.
43. Ashorynejad HR, Shahriari A. Natural convection of hybrid nanofluid in an open wavy cavity. Results Phys. 2018;9:440–55.
44. Mejri I, Mahmoudi A, Abbassi MA, Omri A. LBM simulation of natural convection in an inclined triangular cavity filled with water. Alexandria Eng J. 2016;55(2):1385–94.
45. Sheikholeslami M, Gorji-Bandpy M, Vajravelu K. Lattice Boltzmann simulation of magnetohydrodynamic natural convection heat transfer of Al2O3-water nanofluid in a horizontal cylindrical enclosure with an inner triangular cylinder. Int J Heat Mass Transf. 2015;80:16–25.
46. Hatami M. Numerical study of nanofluids natural convection in a rectangular cavity including heated fins. J Mol Liq. 2017;233:1–8.
47. Saghir M, et al. Two-phase and single phase models of flow of nanofluid in a square cavity: comparison with experimental results. Int J Therm Sci. 2016;100:372–80.
48. Göktepe S, et al. Comparison of single and two-phase models for nanofluid convection at the entrance of a uniformly heated tube. Int J Therm Sci. 2014;80:83–92.
49. Buongiorno J. Convective transport in nanofluids. J Heat Transfer. 2006;128:3.
50. Al JBE. A benchmark study on the thermal conductivity of nanofluids. J Appl Phys. 2009;106:9.
51. Walker KL, Homsy GM. Convection in a porous cavity. J Fluid Mech. 1978;87(3):449–74.
52. Rui Zhang AG, et al. Simulating natural convection and entropy generation of a nanofluid in an inclined enclosure under an angled magnetic field with a circular fin and radiation effect. J Therm Anal Calorim. 2019;139:3803–16.
53. Shantanu Dutta NG, et al. Natural convection heat transfer and entropy generation in a porous rhombic enclosure: influence of non–uniform heating. J Therm Anal Calorim. 2020;020:09634–7.
54. Yuan MA, et al. Koo–Kleinstreuer–Li correlation for simulation of nanofluid natural convection in hollow cavity in existence of magnetic field. J Therm Anal Calorim. 2019;137(4):1413–29.
55. Ahmed Sameh E, et al. MHD natural convection from two heating modes in fined triangular enclosures filled with porous media using nanofluids. J Therm Anal Calorim. 2019;139(5):3133–49.
56. Mehryan SAM, et al. Natural convection of multi-walled carbon nanotube–Fe3O4/water magnetic hybrid nanofluid flowing in porous medium considering the impacts of magnetic field-dependent viscosity. J Therm Anal Calorim. 2019;138(2):1541–55.
57. Hashemi–Tilehnoee1 M et al. Magnetohydrodynamic natural convection and entropy generation analyses inside a nanofluid-filled incinerator-shaped porous cavity with wavy heater block. J Therm Anal Calorim. 2020: 1–3.
58. Selimefendigil Fatih, et al. Natural convection in a CuO–water nanofluid filled cavity under the effect of an inclined magnetic field and phase change material (PCM) attached to its vertical wall. J Therm Anal Calorim. 2018;135(2):1577–94.
59. Dogonchi AS et al. Numerical simulation of hydrothermal features of Cu–H2O nanofluid natural convection within a porous

annulus considering diverse configurations of heater. J Therm Anal Calorim. 2020: 1–7.
60. Matori A, et al. Lattice Boltzmann study of multi-walled carbon nanotube (MWCNT)- Fe3O4/water hybrid nanofluids natural convection heat transfer in a Pshaped cavity equipped by hot obstacle. J Therm Anal Calorim. 2018;136(6):2495–508.
61. Sobhani M. Taguchi optimization for natural convection heat transfer of Al_2O_3 nanofluid in a partially heated cavity using LBM. J Therm Anal Calorim. 2019;138(2):889–904.
62. Abasi ZA, et al. Comprehensive simulation of nanofluid flow and heat transfer in straight ribbed microtube using single-phase and two-phase models for choosing the best conditions. J Therm Anal Calorim. 2019;139(1):701–20.
63. Mostafazadehf Amir, et al. Effect of radiation on laminar natural convection of nanofluid in a vertical channel with single- and two-phase approaches. J Therm Anal Calorim. 2019;138(1):779–94.
64. Etesami N et al. Theoretical comparative assessment of single- and two phase models for natural convection heat transfer of Fe3O4/ethylene glycol nanofluid in the presence of electric field. J Therm Anal Calorim. 2020: 1–2.
65. Mohammad V et al. Two-phase simulation of nanofluid flow in a heat exchanger with a grooved wall. J Therm Anal Calorim. 2020: 1–25.
66. Esmaeili Hossein, et al. Turbulent combined force and natural convection of nanofluid in a 3-D rectangular channel using two-phase model approach. J Therm Anal Calorim. 2018;135(6):3247–57.
67. Siavashi Majid, et al. Numerical analysis of mixed convection of two-phase non-Newtonian nanofluid flow inside a partially porous square enclosure with a rotating cylinder. J Therm Anal Calorim. 2018;137(1):267–87.
68. Zi-Tao Y, et al. A numerical investigation of transient natural convection heat transfer of aqueous nanofluids in a differentially heated square cavity. Int Commun Heat Mass Transf. 2011;38:585–9.
69. Teamah MA, et al. Augmentation of natural convective heat transfer in square cavity by utilizing nanofluids in the presence of magnetic field and uniform heat generation/absorption. Int J Therm Sci. 2012;58:130–42.
70. Ho CJ, et al. Natural convection heat transfer of alumina-water nanofluid in vertical square enclosures: an experimental study. Int J Therm Sci. 2010;49:1345–53.
71. Ho CJ, et al. Numerical simulation of natural convection of nanofluid in a square enclosure: effects due to uncertainties of viscosity and thermal conductivity. Int J Heat Mass Transf. 2008;51:4506–16.
72. Bhuiyana AH, et al. Natural convection of water-based nanofluids in a square cavity with partially heated of the bottom wall. Proc Eng. 2017;194:435–41.
73. Mahian O, et al. Natural convection of silica nanofluids in square and triangular enclosures: theoretical and experimental study. Int J Heat Mass Transf. 2016;99:792–804.
74. Yuan M. LBM simulation of MHD nanofluid heat transfer in a square cavity with a cooled porous obstacle: effects of various temperature boundary conditions. J Therm Anal Calorim. 2019.
75. Abu-Nada H. Numerical study of natural convection in partially heated rectangular enclosures filled with nanofluids. Int J Heat Fluid Flow. 2008;29:1326–36.
76. ÖğÜT EB. Natural convection of water-based nanofluids in an inclined enclosure with a heat source. Int J Therm Sci. 2009;48:2063–73.
77. Rashidi I. Natural convection of Al2O3/water nanofluid in a square cavity: effects of heterogeneous heating. Int J Heat Mass Transf. 2014;74:391–402.
78. Mohamed A, et al. Natural convection heat transfer inside vertical circular enclosure filled with water-based Al2O3 nanofluids. Int J Therm Sci. 2013;63:115–24.
79. Gabriela Huminic AH. A numerical approach on hybrid nanofluid behavior in laminar duct flow with various cross sections. J Therm Anal Calorim. 2020: 1–14.
80. Yu Q et al. Experimental and numerical study of natural convection in bottom-heated cylindrical cavity filled with molten salt nanofluids. J Therm Anal Calorim 2019: 1–13.
81. Farooq H, Ali H, et al. Natural convection of nanoencapsulated phase change suspensions inside a local thermal non-equilibrium porous annulus. J Therm Anal Calorim. 2020: 1–16.
82. Aminossadati SM. Hydromagnetic natural cooling of a triangular heat source in a triangular cavity with water-CuO nanofluid. Int Commun Heat Mass Transfer. 2013;43:22–9.
83. Öztop FS, et al. Natural convection in a flexible sided triangular cavity with internal heat generation under the effect of inclined magnetic field. J Magn Magn Mater. 2016;417:327–37.
84. Mejri I, Mahmoudi A. MHD natural convection in a nanofluid-filled open enclosure with a sinusoidal boundary condition. Chem Eng Res Des. 2015;98:1–16.
85. Chowdhury R, et al. Finite element analysis of double-diffusive natural convection in a porous triangular enclosure filled with Al2O3-water nanofluid in presence of heat generation. Heliyon. 2016;2:8.
86. Sheremet MA, et al. MHD free convection in a wavy open porous tall cavity filled with nanofluids under an effect of corner heater. Int J Heat Mass Transf. 2016;103:955–64.
87. Alsabery AI, et al. Transient natural convective heat transfer in a trapezoidal cavity filled with non-Newtonian nanofluid with sinusoidal boundary conditions on both sidewalls. Powder Technol. 2016;308:214–34.
88. Roslan R, et al. Buoyancy-driven heat transfer in nanofluid-filled trapezoidal enclosure with variable thermal conductivity and viscosity. Numer Heat Transf Part A Appl. 2011;60:67–882.
89. Miroshnichenko IV, et al. MHD natural convection in a partially open trapezoidal cavity filled with a nanofluid. Int J Mech Sci. 2016;119:294–302.
90. Safari MH, et al. Effect of inside heated cylinder on the natural convection heat transfer of nanofluids in a wavy-wall enclosure. Int J Heat Mass Transf. 2016;103:1053–7.
91. Abedini A, et al. MHD free convection heat transfer of a Water-Fe3O4 nanofluid in a baffled C-shaped enclosure. J Therm Anal Calorim. 2018;135(1):685–95.
92. Cho CC. Natural convection heat transfer and entropy generation in wavy-wall enclosure containing water-based nanofluid. Int J Heat Mass Transf. 2013;61(1):749–58.
93. Akter A, et al. Effect of magnetic field on natural convection flow in a prism shaped cavity filled with nanofluid. Procedia Eng. 2017;194:421–7.
94. Zhou L, et al. Natural convection in a cavity with time-varying thermal forcing on a sidewall. Int J Heat Mass Transf. 2020;150:119234.
95. Wenxian Lin S, et al. Prandtl number scalings for unsteady natural convection boundary-layer flow on an evenly heated vertical plate in a homogeneous $Pr > 1$ fluid. Int J Comput Methodol. 2020;76(6):393–419.
96. Ashorynejad HR, Hoseinpour B. Investigation of different nanofluids effect on entropy generation on natural convection in a porous cavity. Eur J Mech B/Fluids. 2016;62:86–93.
97. Mahmoodi M. Numerical simulation of free convection of a nanofluid in L-shaped cavities. Int J Therm Sci. 2011;50:1731–40.
98. Ghasemi S, et al. Natural convection of water-CuO nanofluid in a cavity with two pairs of heat source-sink. Int Commun Heat Mass Transf. 2011;38:672–8.

99. Hejazian M, et al. Natural convection in a rectangular enclosure containing an oval-shaped heat source and filled with Fe3O4/water nanofluid. Int Commun Heat Mass Transf. 2013;44:135–46.
100. Ganji M, et al. Entropy generation of nanofluid in presence of magnetic field using Lattice Boltzmann method. Phys A. 2015;417:273–86.
101. Esfe MH, et al. Natural convection in a trapezoidal enclosure filled with carbon nanotube–EG–water nanofluid. Int J Heat Mass Transf. 2016;92:76–82.
102. Armaghani T. Numerical investigation of water-alumina nanofluid natural convection heat transfer and entropy generation in a baffled L-shaped cavity. J Mol Liq. 2016;223:243–51.
103. Taher Armaghani A. MHD natural convection and entropy analysis of a nano fl uid inside T-shaped baffled enclosure. Int J Numer Methods Heat Fluid Flow. 2018.
104. Ghasemi S, et al. Natural convection cooling of a localised heat source at the bottom of a nanofluid-filled enclosure. Eur J Mech. 2009;28:630–40.
105. Kahveci K. Buoyancy driven heat transfer of nanofluids in a tilted enclosure. J Heat Transf. 2010;132:1–10.
106. Violi K, et al. Natural convection heat transfer of nanofluids in a vertical cavity: effects of non-uniform particle diameter and temperature on thermal conductivity. Int J Heat Fluid Flow. 2010;31:236–45.
107. Jahanshahi M, et al. Numerical simulation of free convection based on experimental measured conductivity in a square cavity using Water/SiO2 nanofluid. Int Commun Heat Mass Transfer. 2010;37:687–94.
108. Mahmoudi AH, et al. Numerical study of natural convection cooling of horizontal heat source mounted in a square cavity filled with nanofluid. Int Commun Heat Mass Transf. 2010;37:1135–41.
109. Ghasemi B, et al. Magnetic field effect on natural convection in a nanofluid-filled square enclosure. Int J Therm Sci. 2011;50:1748–56.
110. Lari K, et al. Combined heat transfer of radiation and natural convection in a square cavity containing participating gases. Int J Heat Mass Transf. 2011;54:5087–99.
111. Alloui Z, et al. Natural convection of nanofluids in a shallow rectangular enclosure heated from the side. The Canadian Journal of Chemical Engineering. 2012;90:69–78.
112. Ashoori Y, et al. Analysis of a fluid behavior in a rectangular enclosure under the effect of magnetic field. World Acad Sci Eng Technol. 2012;6:209–13.
113. Abdollahzadeh M, et al. Free convection and entropy generation of nanofluid inside an enclosure with different patterns of vertical wavy walls. Int J Therm Sci. 2012;52:127–36.
114. Rahimi M, et al. Natural convection of nanoparticle-water mixture near its density inversion in a rectangular enclosure. Int Commun Heat Mass Transfer. 2012;39:131–7.
115. Ahmadi O, et al. Computer simulations of natural convection of single phase nanofluids in simple enclosures: a critical review. Appl Therm Eng. 2012;36:1–13.
116. Kadri S, et al. A vertical magneto-convection in square cavity containing a AL 2O3 + water nanofluid: cooling of electronic compounds. Energy Proc. 2012;18:724–32.
117. Soleimani S, et al. Natural convection heat transfer in a nanofluid filled semi-annulus enclosure. Int Commun Heat Mass Transf. 2012;39:565–74.
118. Rezvani R, et al. Numerical investigation of natural convection heat transfer of nanofluids in a Γ shaped cavity. Superlattices Microstruct. 2012;52:312–25.
119. Rudolf P, et al. Heat transfer enhancement for natural convection flow of water-based nanofluids in a square enclosure. Int J Simul Model. 2012;11:29–39.
120. Raji A, et al. Natural convection heat transfer enhancement in a square cavity periodically cooled from above. Numer Heat Transf Part A Appl. 2013;63:511–33.
121. Ismael A, et al. Conjugate heat transfer in a porous cavity filled with nanofluids and heated by a triangular thick wall. Int J Therm Sci. 2013;67:135–51.
122. Garoosi F, et al. Numerical simulation of natural convection of nanofluids in a square cavity with several pairs of heaters and coolers (HACs) inside. Int J Heat Mass Transf. 2013;67:362–76.
123. Sheikhzadeh GA, et al. Effects of nanoparticles transport mechanisms on Al2O3–water nanofluid natural convection in a square enclosure. Int J Therm Sci. 2013;66:51–62.
124. Kefayati G. Lattice boltzmann simulation of natural convection in partially heated cavities utilizing kerosene/cobalt ferrofluid. 2013;37:107–18.
125. Kefayati GR. Effect of a magnetic field on natural convection in an open cavity subjugated to water/alumina nanofluid using Lattice Boltzmann method. Int Commun Heat Mass Transfer. 2013;40:67–77.
126. Kefayati GHR. Lattice Boltzmann simulation of MHD natural convection in a nanofluid-filled cavity with sinusoidal temperature distribution. Powder Technol. 2013;243:171–83.
127. Cheong HT, et al. Effect of aspect ratio on natural convection in an inclined rectangular enclosure with sinusoidal boundary condition. Int Commun Heat Mass Transf. 2013;45:75–85.
128. Sivaraj S, et al. Coupled thermal radiation and natural convection heat transfer in a cavity with a heated plate inside. Int J Heat Fluid Flow. 2013;40:54–64.
129. Ho CJ, et al. Rayleigh-Bénard convection of Al2O3/water nanofluids in a cavity considering sedimentation, thermophoresis, and Brownian motion. Int Commun Heat Mass Transfer. 2014;57:22–6.
130. Cho CC. Heat transfer and entropy generation of natural convection in nanofluid-filled square cavity with partially-heated wavy surface. Int J Heat Mass Transf. 2014;77:818–27.
131. Malvandi D, et al. Natural convection of nanofluids inside a vertical enclosure in presence of a uniform magnetic field. Powder Technol. 2014;263:50–7.
132. Hosseini M, et al. Nanofluid in tilted cavity with partially heated walls. J Mol Liq. 2014;199:545–51.
133. El-Maghlany WM. Numerical simulations of the effect of an isotropic heat field on the entropy generation due to natural convection in a square cavity. Energy Convers Manag. 2014;85:333–42.
134. Hu Y, et al. Experimental and numerical study of natural convection in a square enclosure filled with nanofluid. Int J Heat Mass Transf. 2014;78:380–92.
135. Öztop HF, et al. A brief review of natural convection in enclosures under localized heating with and without nanofluids. Int Commun Heat Mass Transfer. 2015;60:37–44.
136. Mliki B, et al. Lattice Boltzmann simulation of natural convection in an L-shaped enclosure in the presence of nanofluid. Eng Sci Technol Int J. 2015;18:503–11.
137. Charrada M, et al. Natural convection heat transfer in an enclosure filled with an ethylene glycol—copper nanofluid under magnetic fields. Numer Heat Transf Part A Appl. 2015;67:902–20.
138. Cianfrini C. Natural convection of water near 4 °C in a bottom-cooled enclosure. Energy Procedia. 2015;82:322–7.
139. Škerget J, et al. A numerical study of nanofluid natural convection in a cubic enclosure with a circular and an ellipsoidal cylinder. Int J Heat Mass Transf. 2015;89:596–605.
140. Bakier M. Influence of thermal boundary conditions on MHD natural convection in square enclosure using Cu-water nanofluid. Energy Rep. 2015;1:134–44.
141. Abbassi M, et al. Natural convection in an inclined rectangular enclosure filled by CuO-H2O nanofluid, with

sinusoidal temperature distribution. Int J Hydrogen Energy. 2015;40:13676–84.
142. Jafari M, et al. Lattice Boltzmann simulation of natural convection heat transfer of SWCNT-nanofluid in an open enclosure. Ain Shams Eng J. 2015;6:913–27.
143. Seyyedi SM, et al. Natural convection heat transfer under constant heat flux wall in a nanofluid filled annulus enclosure. Ain Shams Eng J. 2015;6:267–80.
144. Mojumder S, et al. Effect of magnetic field on natural convection in a C-shaped cavity filled with ferrofluid. Proc Eng. 2015;105:96–104.
145. Groşan T, et al. Free convection heat transfer in a square cavity filled with a porous medium saturated by a nanofluid. Int J Heat Mass Transf. 2015;87:36–41.
146. Han X, et al. Buoyancy-driven convection heat transfer of copper–water nanofluid in a square enclosure under the different periodic oscillating boundary temperature waves. Case Stud Therm Eng. 2015;6:93–103.
147. Ismael MA, et al. Nanofluid-saturated porous media and heated by a triangular solid. J Taiwan Institute Chem Eng. 2015;59:138–51.
148. Alsabery AI, et al. Heatline visualization of conjugate natural convection in a square cavity filled with nanofluid with sinusoidal temperature variations on both horizontal walls. Int J Heat Mass Transf. 2016;100:835–50.
149. Raizah A, et al. Double-diffusive natural convection in an enclosure filled with nanofluid using ISPH method. Alexandria Eng J. 2016;55:3037–52.
150. Hussain A, et al. Heatline visualization of natural convection heat transfer in an inclined wavy cavities filled with nanofluids and subjected to a discrete isoflux heating from its left sidewall. Aleandria Eng J. 2016;55:169–86.
151. Mamourian M, et al. Sensitivity analysis for MHD effects and inclination angles on natural convection heat transfer and entropy generation of Al2O3-water nanofluid in square cavity by response surface methodology. Int Commun Heat Mass Transf. 2016;79:46–57.
152. Kolsi L, et al. Computational work on a three dimensional analysis of natural convection and entropy generation in nanofluid filled enclosures with triangular solid insert at the corners. J Mol Liq. 2016;218:260–74.
153. Makulati N, et al. Numerical study of natural convection of a water-alumina nanofluid in inclined C-shaped enclosures under the effect of magnetic field. Adv Powder Technol. 2016;27:661–72.
154. Srivastava S, et al. Interferometric study of natural convection in a differentially- heated cavity with Al2O3-water based dilute nanofluids. Int J Heat Mass Transf. 2016;92:1128–42.
155. Chen S, et al. Double diffusion natural convection in a square cavity filled with nanofluid. Int J Heat Mass Transf. 2016;95:1070–83.
156. Chamkha A, et al. Entropy generation and natural convection of CuO-water nanofluid in C-shaped cavity under magnetic field. Entropy. 2016;18:2.
157. Alsabery AI, et al. Transient natural convective heat transfer in a trapezoidal cavity filled with non-Newtonian nanofluid with sinusoidal boundary conditions on both sidewalls. Powder Technol. 2017;308:214–34.
158. Chamkha AJ, et al. Phase-change heat transfer of single/hybrid nanoparticles-enhanced phase-change materials over a heated horizontal cylinder confined in a square cavity. Adv Powder Technol. 2017;28:385–97.
159. Malik Bouchoucha AE. Natural convection and entropy generation in a nanofluid filled cavity with thick bottom wall: effects of non-isothermal heating. Int J Mech Sci. 2017;126:95–105.
160. Boutra A, et al. Lattice Boltzmann application for a viscoplastic fluid flow and heat transfer into cubic enclosures. Energy Procedia. 2017;139:173–9.
161. Al-Rashed A, et al. Second law analysis of natural convection in a CNT-water nanofluid filled inclined 3D cavity with incorporated Ahmed body. Int J Mech Sci. 2017;130:399–415.
162. Mustafa A. Natural convection in fully open parallelogrammic cavity filled with Cu–water nanofluid and heated locally from its bottom wall. Therm Sci Eng Prog. 2017;1:66–77.
163. Quintino A, et al. Natural convection from a pair of differentially-heated horizontal cylinders aligned side by side in a nanofluid-filled square enclosure. Energy Procedia. 2017;126:6–33.
164. Siavashi K. Lattice Boltzmann numerical simulation and entropy generation analysis of natural convection of nanofluid in a porous cavity with different linear temperature distributions on side walls. J Mol Liq. 2017;233:415–30.
165. Houat B, et al. Mesoscopic study of natural convection in a square cavity filled with alumina-based nanofluid. Energy Procedia. 2017;139:758–65.
166. Chowdhury R, et al. Numerical study of double-diffusive natural convection in a window shaped cavity containing multiple obstacles filled with nanofluid. Procedia Eng. 2017;194:471–8.
167. Bondareva NS, et al. Entropy generation due to natural convection of a nanofluid in a partially open triangular cavity. Adv Powder Technol. 2017;28:244–55.
168. Selimefendigil F, et al. Fluid–structure-magnetic field interaction in a nanofluid filled lid-driven cavity with flexible side wall. Eur J Mech B/Fluids. 2017;61:77–85.
169. Milani Shirvan K, et al. Effects of wavy surface characteristics on natural convection heat transfer in a cosine corrugated square cavity filled with nanofluid. Int J Heat Mass Transf. 2017;107:1110–8.
170. Kanna K, et al. Natural convection on an open square cavity containing diagonally placed heaters and adiabatic square block and filled with hybrid nanofluid of nanodiamond - cobalt oxide/water. Int Commun Heat Mass Transf. 2017;81:64–71.
171. Kolsi L, et al. Control of natural convection via inclined plate of CNT-water nanofluid in an open sided cubical enclosure under magnetic field. Int J Heat Mass Transf. 2017;111:1007–18.
172. Alouah M, et al. Lattice-Boltzmann modeling of natural convection in a cavity with a heated plate inside. Energy Procedia. 2017;139:140–6.
173. Benzema M. Rayleigh-Bénard MHD convection of Al_2O_3–water nanofluid in a square enclosure: magnetic field orientation effect. Energy Procedia. 2017;139:198–203.
174. Salari M, et al. Natural convection in a rectangular enclosure filled by two immiscible fluids of air and Al2O3-water nanofluid heated partially from side walls. Alexandria Eng J. 2018;57:1401–12.
175. Ghalambaz M. Melting of nanoparticles-enhanced phase-change materials in an enclosure: effect of hybrid nanoparticles. Int J Mech Sci. 2017;134:85–97.
176. Ghalambaz M, et al. MHD phase change heat transfer in an inclined enclosure: effect of a magnetic field and cavity inclination. Numer Heat Transf Part A Appl. 2017;71:91–109.
177. Siavashi M, et al. Two-phase mixture numerical simulation of natural convection of nanofluid flow in a cavity partially filled with porous media to enhance heat transfer. J Mol Liq. 2017;238:553–69.
178. Ghadikolaei SS, et al. Analysis of unsteady MHD Eyring-Powell squeezing flow in stretching channel with considering thermal radiation and Joule heating effect using AGM. Stud Therm Eng. 2017;10:579–94.

179. Soltanipour S, et al. Natural convection of Al2O3-water nanofluid in an inclined cavity using Buongiorno's two-phase model. Int J Therm Sci. 2017;111:310–20.
180. Tang W, et al. Natural convection heat transfer in a nanofluid-filled cavity with double sinusoidal wavy walls of various phase deviations. Int J Heat Mass Transf. 2017;115:430–40.
181. Salari M, et al. 3D numerical analysis of natural convection and entropy generation within tilted rectangular enclosures filled with stratified fluids of MWCNTs/water nanofluid and air. J Taiwan Institute Chem Eng. 2017;80:624–38.
182. Rashad AM, et al. Entropy generation and MHD natural convection of a nanofluid in an inclined square porous cavity: effects of a heat sink and source size and location. Chin J Phys. 2018;56:193–211.
183. Sheremet M. Natural convection in an inclined cavity with time-periodic temperature boundary conditions using nanofluids: application in solar collectors. Int J Heat Mass Transf. 2018;116:751–61.
184. Guestal M, et al. Study of heat transfer by natural convection of nanofluids in a partially heated cylindrical enclosure. Stud Therm Eng. 2018;11:135–44.
185. Abbassi MA, et al. Effects of heater dimensions on nanofluid natural convection in a heated incinerator shaped cavity containing a heated block. J Therm Eng. 2018;4:3.
186. Alsabery I, et al. Conjugate heat transfer of Al_2O_3–water nanofluid in a square cavity heated by a triangular thick wall using Buongiorno's two-phase model. J Therm Anal Calorim. 2019;135(1):161–76.
187. Ghalambaz M, et al. Local thermal non-equilibrium analysis of conjugate free convection within a porous enclosure occupied with Ag–MgO hybrid nanofluid. J Therm Anal Calorim. 2019;135:1381–98.
188. Mehryan SAM, et al. Conjugate natural convection of nanofluids inside an enclosure filled by three layers of solid, porous medium and free nanofluid using Buongiorno's and local thermal non-equilibrium models. J Therm Anal Calorim. 2019;135:1047–67.
189. Rahimi A, et al. Lattice Boltzmann numerical method for natural convection and entropy generation in cavity with refrigerant rigid body filled with DWCNTs-water nanofluid-experimental thermo-physical properties. Therm Sci Eng Prog. 2018;5:372–87.
190. Hoghoughi G, et al. Effect of geometrical parameters on natural convection in a porous undulant-wall enclosure saturated by a nanofluid using Buongiorno's model. J Mol Liq. 2018;255:148–59.
191. Al-Kouz WG, et al. Numerical study of heat transfer enhancement for low-pressure flows in a square cavity with two fins attached to the hot wall using Al_2O_3-air nanofluid. Strojniški vestnik-J Mech Eng. 2018;64:26–36.
192. Alsabery AI, et al. MHD convective heat transfer in a discretely heated square cavity with conductive inner block using two-phase nanofluid model. Sci Rep. 2018;8:1.
193. Dogonchi AS, et al. Natural convection analysis in a cavity with an inclined elliptical heater subject to shape factor of nanoparticles and magnetic field. Arab J Sci Eng. 2019;44:7919–31.