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Natural Convection Inside a 3D Regular Shape Enclosures - A Brief Review

Zainab Kareem Ghoben[1,2*], Ahmed Kadhim Hussein[2]

[1] Planning Department, Ministry of Agriculture, Al-Diwaniya 58001, Iraq
[2] Mechanical Engineering Department, College of Engineering, University of Babylon, Babylon 51001, Iraq

Corresponding Author Email: sth.zainab.hussein@student.uobabylon.edu.iq

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ABSTRACT

This paper introducing a review of the recent three-dimensional numerical and experimental researches on the laminar natural convection heat transfer inside cavities. Focusing on the previous research's cavity geometry specially the regular shapes both simple or complex shapes. A wide variety of geometries which having different inclinations, inserted bodies and boundary conditions were presented and discussed. The working fluids of the cavities were also reviewed, classical fluids, nanofluids and else. It can be concluded that there is a gap in the research region of the three-dimensional numerical studies in complex cavities. And generally, lake in the experimental studies for all cavity geometries classical or complex were appointed.

1. INTRODUCTION

The widespread applications of the natural convection or buoyancy driven heat transfer and fluid flow inside cavities lead to the clear attention received over the recent years [1-10]. This field was investigated numerically and experimentally. Where the increasing importance of the computer techniques for modelling and simulation allows a quantitative and qualitative evaluation of the different complex phenomenon. Many works in the current field were viewed for different geometries of the cavities; square or non-square [11-17]. The accomplished cases were studied under various conditions which was enhancing the heat transfer. Different techniques were presented, which able to enhance the heat transferred through the cavities by natural convection. These techniques were either changing the shape or inclination of the cavity. Bairi [9] and Majdi et al. [18] used different inclination angles for their parallelogrammical cavities. While Al-Rashed et al. [19-21] works on inclined cubical cavity whereas Hussein et al. [22] cavity was an inclined trapezoidal one. On the other hand, adding fins inside the closed cavities was one of these techniques [3]. Ma et al. [23] added a square fin inside his closed cavity. The fins used by other researcher were varied in location and shape. A rectangular shape fin was used by Charazed and Samir [24] while different shapes were fabricated by Saeid [25]. Which was rectangular, one triangular, two opposite triangular and two isosceles triangular shapes. These fins or baffles were either rigid or sometimes porous like those of Asl et al. [26]. Also, Siavashi et al. [27] cavity was embedded with an array of porous fins.

Enhancing the working fluid properties by using various (Ra) was considered a technique also. The laminar natural convection (Ra) range was ($10^3 \leq Ra \leq 10^6$) and else [28-31]. Recently, using the fluid additives was a common technique in this field. Adding nanoparticles to the classical base fluids improving the fluid thermal properties and the heat transfer performance [32-36]. Researchers approved that the thermal properties were enhanced by adding the nanoparticles of metals or other materials by a specific volume fraction range [37-39]. This range was not to exceed ($0 \leq \varphi \leq 0.06$). Where this range was ideal to get the enhancement of two-phase fluids and avoiding the problems of agglomeration or dissipation of the solid particles at the same time [40]. Sometimes using the external magnetic field enhancement scheme is one of these techniques [14, 41]. Which is of higher importance due to its wide application in metal casting and other industrial applications [42-44]. From other side, number of researchers depend on the advantages of the porous media expected advantages in designing their cavities [45-47]. The present work, introduced a detailed literature review on the specific research region of the three-dimensional numerical and experimental natural convection heat transfer inside cavities for different geometries, boundary conditions and filled with different working fluids, classical or nanofluids.

2. NATURAL CONVECTION INSIDE CLASSICAL GEOMETRY CAVITIES

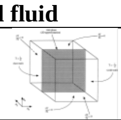
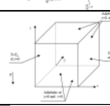
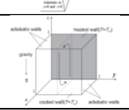
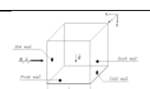
The natural convection heat transfer in three dimensional square and rectangle cavities had been studied numerically and experimentally for different working fluids, classical and nanofluids. Table 1 below display the previous numerical studies for classical fluids [48-65] which consists of only one material and nanofluids [66-80] which was consists of classical fluid as base fluid and nanoparticles of other solid material; while experimentally [81-85] and [86-90] for classical and nanofluids respectively.

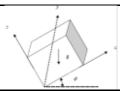
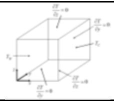
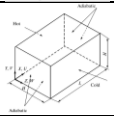
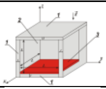
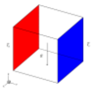
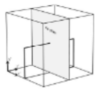
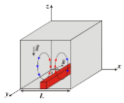
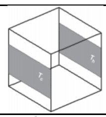
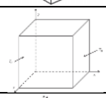
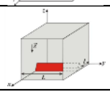
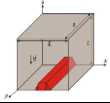
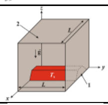
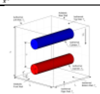
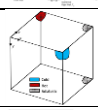
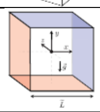
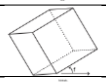
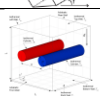
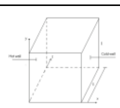
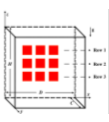
2.1 Numerical studies inside classical geometry cavities with classical working fluids

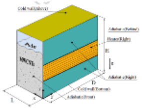
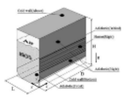
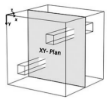
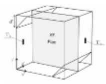
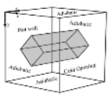
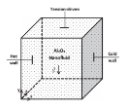
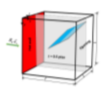
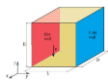
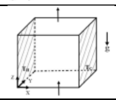
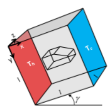
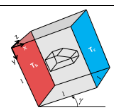
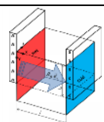
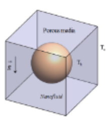
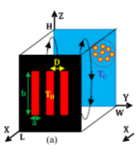
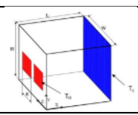
This study focusing on the last six years of research. While there were many older studies for the 3D natural convection inside classical geometry cavities like those included in references [48-54] which were described novel and advanced numerical techniques to describe and solve problems of this field. Recently for the 3D simple classical cubical cavities numerical studies, Li et al. [55] predicted a three types of natural convection problems in cavity filled with air. Two opposite vertical walls were kept at different temperatures, while the remained four walls were either adiabatic for the first type or have linear temperature variations for the second type. Whereas the third type, the front and back surfaces have linearly variable temperature. The bottom and top surface were adiabatic. The results showed that the third type exhibited more general three-dimensional characters. Kolsi et al. [56] proposed the natural convection and the generated entropy and internal heat generation. A partial cooler was located on the insulated bottom wall and the cavity was heated differentially while the horizontal walls were adiabatic. It was found that the role of location and height of the partition became less important with increasing the internal (Ra). Bondareva and Sheremet [57] discussed the convective heat transfer combined with melting of pure gallium. The vertical surfaces were at low constant temperature while the other walls adiabatic. A constant temperature heat source was placed on the bottom wall. A uniform but inclined magnetic field affects the melting process inside the cavity. The results obtained that the magnetic field intensity growth reflected the convective flow suppression and heat transfer rate reduction. Higher values of Hartmann number homogenized the liquid flow and the heat transferred inside the melting zone.

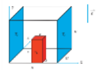
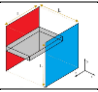
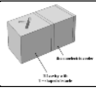
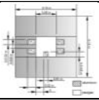
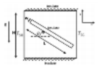
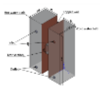
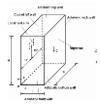
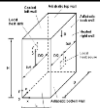
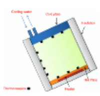
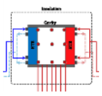
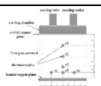
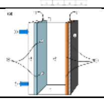
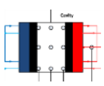
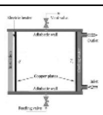
Al-Rashed et al. [30] investigated the air heat convection, where the cavity was heated partially for different sidewall arrangements. A part of the left vertical sidewall was kept at isothermal cold temperature, whereas a part of the right sidewall was kept at isothermal hot temperature. The other walls were considered adiabatic. The results showed that the middle-middle arrangement of heating and cooling regions produced higher values of the average (Nu). Also, for air Wang et al. [58] performed a study for the natural convection in a differentially heated cavity using the recently developed coupled discrete unified gas-kinetic scheme. The founded results showed that the temperature and the velocity boundary layers were grew adjacent to the isothermal walls, and became thinner as (Ra) increase. Whereas no boundary layer appeared near the adiabatic walls. Finally, an exponential scaling law between (Nu) and (Ra) was suggested. Gibanov and Sheremet [59-61] solved the natural convection for a cavity equipped by a hot partition as a heat source having a triangular cross section. The vertical opposite walls were cooled while the rest walls were adiabatic. It was found that the extreme position on the left side of the heater illustrated the more essential cooling of the cavity [59]. After this, investigation of five various shapes of the heater cross section were performed [60]. Namely as rectangular, three trapezoidal and one triangular. It has been found that the trapezoidal shapes were more effective with respect the highest heat removed. At last, the team founded that the variation of geometrical parameters of the trapezoidal cross section have a clear effect. The parameters like height, length and size influenced the evolution of the temperature and fluid flow fields inside the enclosure. Spizzichino et al. [62] investigated the natural convection flow of air in a cold enclosure containing a tandem of cold and hot vertically aligned cylinders. It was found that the distance between the cylinders controlling the determination of the characteristics of instability mechanisms. Alnaqi et al. [31] solved the air natural convection inside lateral active walls cavity. Both the vertical front and right sidewalls maintained at a constant cold temperature. While an isothermal hot temperature applied for both the vertical back and left sidewalls. The upper and lower walls were adiabatic. To achieve that increasing the (Ra) led to increase of the average (Nu) and decrease of the (Ha). While Fabregat and Pallares [63] cavity was heated by imposing a constant temperature at the bottom walls and cooled by imposing a constant temperature at the top walls. The front and back walls were considered adiabatic. It was found that the resulting characterization of the near-wall flow allowed to derive new semi-analytical models for wall transfer applications in enclosed cavities containing air. Another study by Alshomrani et al. [64] predicted the natural convection of air inside inclined cavity with different locations of the heater and coolers. The left and right walls were cooled partially whereas the other walls adiabatic. In the left and right walls, three unlike locations of the cooler were examined. Whereas the heater moved in three locations in the middle of the enclosed cavity. It was found that the inclination of the enclosure and the locations of the coolers influence the stream and energy transport strongly. Zemach et al. [65] like Spizzichino et al. [62] immersed a tandem of hot and cold but horizontally aligned cylinders inside a cold cavity filled with air. It was found that the spacing of the cylinders affecting the transition of the flow from steady to unsteady flow.

Table 1. Classical geometry cavities

Author Year	Fluid type Parameters	Shape	Conclusions
	Numerical / Classical fluid		
[48] 2000	Air $10^3 \leq Ra \leq 10^7$		Spatial resolution of the data better than 0.02% at highest Ra.
[49] 2003	Air $10^3 \leq Ra \leq 10^5$		The model simple and easy for implementation.
[50] 2003	Air $10^4 \leq Ra \leq 10^6$		This method very efficient and useful for checking the accuracy of any numerical method.
[51] 2004	- $Ra \leq 10^6$ $1 \leq AR \leq 20$	High AR enclosure	2D approximation deviates from 3D.
[52] 2007	Molten metal Pr = 0.054		Magnetic field controlling the stabilization phenomena.

[28] 2009	- $10^3 \leq Ra \leq 10^6$ $0^o \leq \theta \leq 90^o$		DQ / velocity-vorticity succeeded in simulate 2D and 3D.
[53] 2009	- $10^3 \leq Ra \leq 10^5$		Two LBM models combination gives excellent agreement with previous studies.
[29] 2011	- $10^3 \leq Ra \leq 10^6$ $0.1 \leq AR \leq 5$		Heat transferred through cavities of $AR \geq 1$ was conservative to the action of the secondary flow.
[54] 2014	Air $10^3 \leq Ra \leq 10^5$		Average Nu is an increasing function of (Ra, k ratio) and decreasing of the emissivity. While radiative Nu is increasing function of it.
[55] 2016	Air $10^4 \leq Ra \leq 10^5$		MRT model has more advantages than the others.
[56] 2016	- $10^3 \leq Ra_E \leq 10^5$ $10^3 \leq Ra_I \leq 10^6$ h=0.25, 0.5, 0.75 c=0.25, 0.5, 0.75		The role of location and height of partition become less important with increasing Ra_I.
[57] 2017	Gallium $Ra = 7.17\times10^5$ Ha = 0, 50, 100 $\alpha = 0^o$ $0 \leq \gamma \leq \pi/2$		High values of Ha homogenize the flow and heat transfer.
[30] 2017	Air $10^3 \leq Ra \leq 10^6$		The middle-middle arrangement of heating and cooling regions produces higher average Nu.
[58] 2017	Air $10^3 \leq Ra \leq 10^{10}$		T and v boundary layers were developed adjacent to the isothermal walls and become thinner as Ra increases.
[59] 2017	Newtonian fluid $10^4 \leq Ra \leq 10^6$ $0.05 \leq l/L \leq 0.35$		The extreme left position of the heater illustrates more cooling.
[60] 2018	Newtonian fluid $10^4 \leq Ra \leq 10^6$ $\pi/4 \leq \alpha \leq \pi/2$		Trapezoidal shape of heater was the more effective.
[61] 2019	Newtonian fluid $10^4 \leq Ra \leq 10^6$		The variation of height, length and size of the heater influences the temperature and fluid flow.
[62] 2019	Air $10^4 \leq Ra \leq 10^6$		The distance between the cylinders plays an important role in the instability mechanisms.
[31] 2020	Air $10^3 \leq Ra \leq 10^6$		Increase Ra leads to increase average Nu and decrease Be.
[63] 2020	Air $10^5 \leq Ra \leq 5.4\times10^8$		The resulting characterization of the near-wall flow allows to derive semi-analytical models for wall heat transfer.
[64] 2020	Air $10^3 \leq Ra \leq 10^6$		The inclination of and the locations of the coolers influence the stream and energy transport.
[65] 2021	Air $Ra= O(10^6)$		The distance between the cylinders effects the transition to unsteady flow.
Numerical / Nanofluid			
[66] 2014	Al_2O_3-water $10^3 \leq Ra \leq 10^6$ $0\% \leq \varphi \leq 20\%$		Average Nu increases with φ and Ra while Be is revers to Nu.
[67] 2016	Cu-water Al_2O_3-Water $10^5 \leq Ra \leq 10^7$ $0 \leq \varphi \leq 0.01$ $1 \leq AR \leq 7.5$		Cu–water nanofluid has the greatest effect.

[68] 2016	Air MWCNTs-water $10^3 \leq Ra \leq 10^6$ $\varphi = 0.002, 0.004, 0.01$ $AR = 0.125, 0.25, 0.375, 0.5$		The interface AR influences the fluid flow, heat transfer and entropy generation.
[69] 2017	Air MWCNTs-water $10^3 \leq Ra \leq 10^6$ $\varphi = 0.002, 0.01$ $r = 0, 0.15, 0.20, 0.25$		Curved corner is effective method to control fluid flow and energy consumption.
[70] 2016	Al_2O_3-water $10^4 \leq Ra \leq 10^5$ $0 \leq \varphi \leq 0.15$ $L_B/L = 1/4, 1/2, 1/8$		Average Nu rose by increase Ra and φ while declined with block size increase.
[71] 2016	- $10^4 \leq Ra \leq 10^6$ $0 \leq \varphi \leq 0.15$ $0.01 \leq R_c \leq 100$		The partition is a control parameter for heat, fluid flow and energy consumption.
[72] 2016	Al_2O_3-water $10^3 \leq Ra \leq 10^6$ $0 \leq \varphi \leq 0.15$		Circulation inside the enclosure is a function of the geometrical parameters of the inserted body.
[37] 2016	Al_2O_3-water $Ra=10^5$ $0 \leq \varphi \leq 0.2$ $-10^3 \leq Ma \leq 10^3$		The intensity of the flow increases by increasing φ. By increasing the Ma, Nu increases.
[73] 2017	CNT-water $10^3 \leq Ra \leq 10^5$ $0 \leq \varphi \leq 0.05$ $0 \leq Ha \leq 100$ $0^o \leq \phi \leq 360^o$		The maximum heat transfer occurs at 180º, and minimum at 270º.
[38] 2017	CuO-water $10^3 \leq Ra \leq 10^6$ $0 \leq \varphi \leq 0.04$		Average Nu enhances with Ra and φ increase.
[74] 2017	Seawater-Al_2O_3 $10^5 \leq Ra \leq 10^6$		The Lorentz force has no significant effect on the flow.
[19] 2017	CNT-water $10^3 \leq Ra \leq 10^5$ $0 \leq \varphi \leq 0.05$ $0^o \leq \phi \leq 180^o$ $0.01 \leq R_c \leq 100$		Maximum average Nu occurs at angle of inclination of 30° and 150°.
[20] 2017	CNT-water $10^3 \leq Ra \leq 10^5$ $0 \leq \varphi \leq 0.05$ $0^o \leq \phi \leq 180^o$		Entropy declines when inclination angle increased up to 90°.
[75] 2018	CNT-water $0 \leq \varphi \leq 0.05$ $0 \leq Ha \leq 100$ $0 \leq L_B \leq 1$		Location of magnetic field plays important role even at same Ha.
[76] 2018	Al_2O_3-water $10^3 \leq Ra \leq 10^5$ $\varphi = 0.04$ $0 \leq Ha \leq 60$ $0.001 \leq Da \leq 100$		Thermal boundary layer becomes thicker with augment of Ha but it has opposite behaviour for Da.
[77] 2020	Cu-water Al_2O_3-water Ag-water TiO_2-water $10^3 \leq Ra \leq 10^6$ $0 \leq \varphi \leq 0.1$ $0 \leq R_d \leq 0.5$ $\gamma = 0^o, 45^o, 90^o$		The total Nu increases with φ, radiation parameter and AR of the heating elements. No considerable effect of γ.
[78] 2020	Al_2O_3-water $10^3 \leq Ra \leq 10^6$ $0 \leq \varphi \leq 0.1$		Increasing the heating section size and Ra increases the heat removed by same nanofluid.

[79] 2020	Cu-water $10^3 \leq Ra \leq 10^6$ $0 \leq \varphi \leq 0.1$		The increase of the heating section size and Ra leads to increase of heat transfer.
[39] 2020	CuO-water $10^3 \leq Ra \leq 10^5$ $0 \leq \varphi \leq 0.03$		At low Ra the isotherms become uniform. At higher Ra, this uniformity reduces.
[80] 2020	CNT-water $0 \leq \varphi \leq 0.04$		The size and inclination of the T obstacle have slight effect on the variation of Nu.
Experimental / Classical fluid			
[81] 2016	Air $10^4 \leq Ra \leq 10^5$ D = 0.4, 0.5, 0.6		0.4 position of the hot source was the best to remove the heat generated in the cavity.
[82] 2017	Air $1.5\times10^5 \leq Ra \leq 4.5\times10^5$ $0^o \leq \phi \leq 90^o$		The maximum and minimum heat transfer occur at tilt angles of 45°and 90°.
[83] 2018	Deionized water Ra = 7.05×10^5, 4.27×10^6, 1.84×10^7		The technique very robust and high accuracy in temperature measurement (within 1%).
[84] 2018	Air $1.6\times10^5 \leq Ra \leq 4.67\times10^7$ $1 \leq AR \leq 6$		The mean Nu increases from 23.63 to 73.35 with decreasing AR from 6 to 1.
[85] 2019	Air $4.51\times10^5 \leq Ra \leq 1.13\times10^8$ $1 \leq AR \leq 6$		Nu decreases when the heated wall temperature changed from constant to sinusoidally varying.
Experimental / Nanofluid			
[86] 2014	Al_2O_3, TiO_2, CuO with Turbine oil φ = 0.2%, 0.5%, 0.8% $\theta = 0^o, 45^o, 90^o$		At 90º maximum Nu was for TiO_2 at φ = 0.2% while it was for CuO at φ = 0.8%.
[87] 2017	De-DI water Al_2O_3-water $0 \leq \varphi \leq 0.006$ AR (1, 2, 4)		The optimum concentration for maximum heat transfer varies with AR.
[88] 2017	Ag-water (distilled) φ = 0.1%vol $5^o \leq \Delta T \leq 25^o$		The heat transfer depends on Nu, the flow structure and magnetic field.
[89] 2019	SiO_2-water $2.3^o \leq \Delta T \leq 30.9^o$		Increasing Ra increases Nu and inclination effect is higher at low nanofluid loading.
[90] 2020	Al_2O_3-MWCNT-water (hybrid) $1.65\times10^8 \leq Ra \leq 3.8\times10^8$ Al_2O_3: MWCNT (80:20, 60:40, 20:80)		The engagement of two nanofluids improved natural convection performance.
[91] 2020	Cu-water φ = 0.001, 0.005, 0.01, 0.02, 0.04		The strong magnetic field making negative behaviour of nanoparticles on the heat transfer.

2.2 Numerical studies inside classical geometry cavities with nanofluids working fluids

To enhance the natural convection inside cavities, researchers depended on the additives to the working fluids, using different particles to form a high thermal properties nanofluids [66-80]. Where Kolsi et al. [66] studied the natural convection of the Al_2O_3-water nanofluid. The left and right sidewalls of the cavity were kept at isothermal hot and cold temperature respectively. The other walls kept adiabatic. The results explained that the average (Nu) increases with the nanoparticles solid volume fraction and (Ra) increase. While the (Be) had a reverse behavior to that of the average (Nu). Purusothaman et al. [67] studied the Cu-water and Al_2O_3-water nanofluids natural convection in a cooling equipment. A (3×3) array of constant heat heaters was placed on a single vertical wall of the enclosure. It was observed that Cu–water nanofluid had the greatest effect on the performance of the cooling equipment compared to the other one. And the row averaged (Nu) increased in monotony with the increase in both (Ra) and the nanoparticle solid volume fraction. Salari et al. [68-69] reported results for the natural convection and entropy generation for enclosure with layered fluid system. The enclosure was differentially heated from sides and filled by two immiscible gas/liquid fluids (air/MWCNTs-water). Two heaters with constant heat flux were placed at the sides. The top and bottom walls were kept at constant cold temperature. These results showed that the total entropy generation and the mean (Nu) were reduced by increasing of nanofluid interface (AR) and enhanced by increasing the (Ra) [68]. By repeating their study within the enclosure with fillets, getting that the curved corners were effective method in controlling fluid flow and energy consumption [69].

Kolsi et al. [70] presented a simulation of the Al_2O_3–Water nanofluid natural convection and entropy generation. The cavity containing twin adiabatic blocks. The vertical walls were differentially heated. The results showed that the average (Nu) rose with the increase in (Ra) and volumetric fraction of solid particles and declined with the increase in block size. Again, Kolsi et al. [71] inserted solid inserts having triangular cross section at the corners of the cavity. Based on the number and location of these inserts, three cases were studied. It was observed for any case, the partitions can be used as control elements for heat, fluid flow and energy consumption. At the same time, Kolsi et al. [72] inserted an adiabatic diamond shaped obstacle in open cavities. Approving that the geometry of the partition was an important parameter controlling the heat and the fluid flow inside open enclosures also. For the same cavity shape, heating conditions and the nanofluid fills. But the top surface of the liquid was free and in contact with the gas above Kolsi et al. [37] founded that by increasing the (Ma), the (Nu) increases. Finally, Kolsi et al. [73] solved the magneto hydrodynamic natural convection in an open enclosure but filled with CNT-water nanofluid. The cavity was heated as like as kolsi's previous conditions [71-72] and an inclined plate with finite length was attached inside it. It was observed that the maximum heat transfer was formed when the angle of the fin was 180º but minimal value of the average (Nu) was changed according to the nanoparticle addition.

Rahimi et al. [38] investigated the CuO-water nanofluid heat convection. The vertical walls of the cavity were heated differentially while the remained walls were insulated. The results showed that the average (Nu) enhances with increasing the (Ra) and the nanoparticle volume fraction. On the same heating conditions of cavity but filled with seawater and Al_2O_3 nanoparticles Jelodari and Nikseresht [74] studied the effects of Lorentz force and magnetic field-based inductive field on the thermal performance. Indicating that the Lorentz force had no significant effect on the flow. But increasing the nanoparticle to 2% had a significant effect on the Lorentz force magnitude. While increasing it to 6% tended to shift the free convection to conduction heat transfer. Al-Rashed et al. [19] evaluated the natural convection of CNT-water inside an inclined cavity. The cavity was heated differentially while the other walls were adiabatic. A conductive Ahmed body was mounted at the center of the enclosure. It was founded that the entropy declined when the inclination angle of the cavity increased up to 90°, after that entropy generation surges. Then, Al-Rashed et al. [20] results showed that the CNT particles enhanced the heat transfer in all the considered cases. The maximum average (Nu) was reported when the angle of inclination was 30° and 150°. And the variation in thermal conductivity ratio had a least effect on convection. Then, the effects of partially active magnetic field on natural convection heat transfer inside the same cavity conditions but without inclination or immersed body were studied by Al-Rashed et al. [75]. Two cases were considered to discover this effect. The magnetic field was applied to the upper half of the cavity firstly and then to the lower half. The remaining walls were kept insulated. It was found that the location of the magnetic field played an important role even for the same (Ha). Thus, it can be a good parameter to control heat and fluid flow inside the closed space.

Sheikholeslami et al. [76] investigated the roles of the magnetic field on the free convection of Al_2O_3-water in a cold porous cavity with hot sphere obstacle. Results indicated that the Lorentz forces made the temperature gradient decrease. Also, the thermal boundary layer becomes thicker with augment of (Ha) but opposite behavior was observed for (Da). Moutaouakil et al. [77] cavity was heated by using three identical and parallel elements on the left vertical sidewall. These elements were had three inclinations (0°, 45°, 90°). The cavity filled with different water based nanofluids, the nanoparticles were (Cu, Al_2O_3, Ag, TiO_2). The effect of the spacing of the heating elements and their (AR) were discovered to investigate the effect of the thermal radiation on the natural convection. The results showed that no detected effect of the elements inclination on the average (Nu). While increasing the radiation parameter and the (AR) causing the heat transfer to increase. Sannad et al. [78-79] uses two different heat sources to deal with the heat convection inside cavity. The first was the partially heated left side wall [78] while the second was by using a partition maintained at a hot and uniform temperature [79]. In order to understand the effect of the nanofluid on the mechanism of natural convection for the flow of (Al_2O_3, Cu and TiO_2) water based nanofluids. It was found that the increase of the heating section size and (Ra) increases the amount of heat removed by the same nanofluid [78]. While the Cu based nanofluid guarantees the best thermal heat transfer [79]. Esfe et al. [39] solved the natural convection of CuO-water nanofluid inside a cavity equipped with 1, 2 and 3 porous fins. The cavity was heated differentially. It was founded that for low (Ra), the isotherm lines were rather uniform. While at higher (Ra), the augmentation of buoyancy force strongly reduces the isotherms uniformity. Another classical cavity shape was investigated by Selimefendigil and Oztop [80]. It was rectangular with one inclined side wall having inner inclined T-shaped heat source. The inclined sidewall was kept at the higher temperature while the opposite vertical wall kept at the lower one. The results indicated that the size and the inclination of the obstacle had slight effects on the variation of the (Nu). Where a maximum deviation of 6% in the average heat transfer was obtained when the orientation changed from -45° to -90°. When the minimum and maximum values of cavity inclination angles are compared, 23.70% of reduction in the average (Nu) was obtained.

2.3 Experimental studies inside classical geometry cavities with classical working fluids

The field of natural convection heat transfer inside cavities as like as all original physical fields was investigated experimentally. Where Nardini et al. [81] accomplished the natural convection in a square cavity with partially active thermal side walls numerically and experimentally. Four cold sources placed on the vertical walls and additional active hot source placed on the bottom wall. The experimental analysis was carried out through the holographic interferometry. Three different positions of the hot source were investigated. The results clearly showed that these positions have an effect on the heat transferred. The best position of the hot source was at 0.4 corresponds to the middle of the bottom wall, which created the fastest velocity field that able to remove the heat generated in the cavity. Mahmoudinezhad et al. [82] also visualized the laminar free convection heat transfer in a partitioned cavity both experimentally and numerically. The cavity with adiabatic and isothermal horizontal side walls. The experiments were carried out using the Mach-Zehnder interferometer. The cavity was separated into two identical parts by a horizontal and adiabatic inclined partition. The results showed that the average (Nu) and the heat transfer enhanced as the (Ra) increased. For a given (Ra) the maximum and the minimum heat transfer occurred at (45° and 90°) of the partition inclination angle, respectively. Based on the experimental data, a new correlation that represented the average (Nu) of the heated walls as function of the (Ra) and the inclination angel of the partition was proposed. Bharti et al. [83] used the Z-type schlieren technique to visualize the natural convective flow of the de-ionized water inside a cubical cavity heated differentially. For simultaneous measurement of ray-averaged velocity as well as temperature fields beside qualitative flow visualization. The velocity field was also determined by using laser-based particle image velocimetry to compare with schlieren based technique. The obtained results can be confidently used as benchmark data for simulation purpose using water as a fluid medium. The results obtained via experiments were in a good agreement with those of computational results that gave confirmation of the effectiveness of the proposed method. While Karatas and Derbentli [84-85] evaluated the natural convection and radiation in rectangular cavities with different (AR). The cavities had different lengths. The cavity was closed, filled with air, and has one active vertical wall. The opposing vertical wall was inactive. The other four walls were adiabatic. The results recognized that the mean (Nu) increased from 23.63 to 73.35 with decreasing the (AR) from 6 to 1 [84]. Then, founded that the (Nu) largely decreased when the temperature on the heated wall changed from constant to sinusoidally varying [85].

2.4 Experimental studies inside classical geometry cavities with nanofluid working fluids

Heris et al. [86] investigated the inclination angle of the cavity effect on the natural convection. The side length of the cubic cavity was 10 cm filled with different working fluids Al_2O_3, TiO_2 and CuO within turbine oil. Founded that for inclination angle of 90°, for volume fraction 0.2%, the maximum (Nu) was that of TiO_2 nanoparticles. While for 0.8% the CuO nanoparticles enhances the (Nu) was the best. Solomon et al. [87] accomplished the influence of the (AR) of a rectangular cavity but filled with nanofluids. It was found that the proper design of the cavity saved plenty of energy, as losses were minimized. Where the (AR) of the cavity has a significant effect on the heat transfer coefficient and the (Nu). The ideal nanofluid concentrations for maximum heat transfer were varied with the cavity (AR). And noticed that the (Ra) had a strong effect on the (Nu). Whereas Roszko and Wajs [88] proposed the multi-stage approach to achieve the thermo-magnetic convection of diamagnetic fluids in the Rayleigh-Benard configuration in cubical enclosure. The heat transfer analysis showed dependence of the (Nu) on the flow structure and at the same time on the magnetic field. It can be found that imposed magnetic field changed the energy transfer within the system. Torki and Etesami [89] studied the heat transfer in a rectangular enclosure at different inclinations and concentrations of SiO_2-water. Results indicated that the heat transfer had no significantly changed for low concentrations of nanofluids. However, for solid volume fraction greater than 0.005 the heat transfer coefficient decreased with concentration of nanofluid. Also, it was found that at low concentrations of nanofluid, the effect of tilt angle on (Nu) was more pronounced. As like as Solomon et al. [87] experimental rig, Giwa et al. [90] accomplished the natural convection of hybrid nanofluids inside a square cavity. A direct relationship was noticed between the (Ra) and the average (Nu). The temperature gradient, the percent weight of bi-nanoparticles were observed to augment the average of (Nu, h, and Q). A maximum enhancement of 16.2%, 20.5%, and 19.4% were recorded for these averages, respectively, in relation to the base fluid. A new correlation related to the (Ra) and the bi-nanoparticles ratio has been developed for predicting the average (Nu). Results from their study introduced the advantages gated by the hybrid nanofluid over the single-particle nanofluid. Kargarsharifabad [91] visualized the natural convection of Cu-water nanofluid inside a cubic enclosure experimentally and numerically. The flow was under the effects of both the time-unvarying and alternating magnetic fields. The results showed that in the absence of a magnetic field, adding Cu-nanoparticles to the water enhanced the heat transfer performance where the (Nu) was increased. On the other hand, increasing the nanoparticles volume fraction reduces the heat transfer performance if the magnetic field strength was beyond a threshold value of the (Ha).

3. NATURAL CONVECTION INSIDE COMPLEX GEOMETRY CAVITIES

In general, the complex cavities, **which is not cubical in shape** are less in researches specially the three-dimensional studies, where these shapes studied briefly in two dimensions as reported in references [1, 3, 7]. The 2D studies on parallelogrammical cavities [92-94], trapezoidal [95-98], triangular [99-101], and other irregular shapes [102-104]. While it was founded a few studies in three dimensions just that was presented in Table 2.

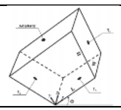
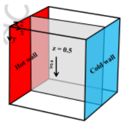
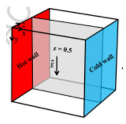
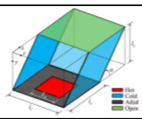
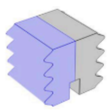
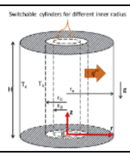
3.1 Numerical studies inside complex geometry cavities

For classical fluids specifically air, Hussein et al. [22] cavity was inclined trapezoidal containing air. The unsteady laminar 3D natural convection and entropy generation were performed. The vertical right and left sidewalls of the cavity were maintained at constant cold temperatures. The lower wall was subjected to a constant hot temperature, while the upper one was considered insulated. The results showed that when the (Ra) and the flow circulation increased, the flow patterns were changed especially in 3D. Also, the inclination angle effects on the total entropy generation becomes insignificant when the (Ra) was low. When the (Ra) increases the average (Nu) increases also. While for nanofluids, Al-Rashed et al. [105] investigated the parallelogrammical shape cavity. Taking the effect of the angle of inclination of the external magnetic force on the entropy generation due to the natural convection inside a cubical cavity. The cavity was filled with CNT-water nanofluid. The vertical walls of enclosure were differentially heated and the horizontal were kept adiabatic. The results showed that the effect of the inclination angle was more pronounced when the (Ra) equals (10^5). Then Al-Rashed et al. [106] founded that the heat transfer intensified with increasing the percentage of CNT particles and a larger (Ra). The repelling effect of the magnetic force inhibited the heat transfer by 50% when the (Ha) increased as (50-100). Al-Rashed et al. [21] studied the natural convection in a 3D parallelogrammical top side opened cavity filled with Al_2O_3-water nanofluid with partially heated square at the bottom side while the remaining part of it was considered adiabatic. The main obtained results showed that the inclination angle of the back and front walls and nanoparticle volume fraction affect the flow structure and enhanced the heat transfer. Whereas Bendrer et al. [107] cavity was wavy cubical. The flow was partitioned into two layers; porous and hybrid nanofluid layers. The upper and lower plans of the domain were kept adiabatic while the other plans were maintained at low temperature. A rectangular heated area was located in the bottom plane. The magnetic force effect was taken into account. Their results showed that changing the location of the heated area was a beneficial factor in convection results. Also, when (Ha) was changed from (0-100), a drop of the stream function was appointed as 84.78%.

3.2 Experimental studies inside complex geometry cavities

Pena et al. [108] visualized the natural convection of mineral oil based nanofluids when it used as a cooling fluid. This system consists of a closed cavity had a vertical annular shape. It was filled with two types of nanoparticles (AlN and TiO2) of different concentrations. The inner cylinder works as a constant heat source while the outer cylinder removes the energy with a constant temperature condition. Correlations for the (Nu) in terms of (Ra) were obtained for different nanoparticle concentrations. Under certain conditions, enhancements in heat transfer coefficients were found when using nanofluids when compared to base fluid.

Table 2. Complex geometry cavities

Author Year	Fluid type Parameters	Shape	Conclusions
	Numerical / Classical fluid		
[22] 2016	Air $10^3 \le Ra \le 10^5$ $0^o \le \phi \le 180^o$		The inclination angle insignificant on the entropy generation when Ra low.
	Numerical / Nanofluid		
[105] 2017	CNT-water $10^3 \le Ra \le 10^5$ $0 \le \varphi \le 0.05$ $0 \le Ha \le 100$ $0^o \le \alpha \le 90^o$		Entropy generation shifted towards vertical and horizontal walls when the angle of the magnetic field increased.
[106] 2018	CNT-water $10^3 \le Ra \le 10^5$ $0 \le \varphi \le 0.05$ $0 \le Ha \le 100$ $0^o \le \alpha \le 90^o$		The effect of the magnetic force inhibits the heat transfer by 50% if Ha increased (50-100).
[21] 2019	Al_2O_3-water $10^3 \le Ra \le 10^5$ $0 \le \varphi \le 0.05$ $5^o \le \phi \le 75^o$		The inclination angle of the back and front walls and φ effect the flow structure and enhance the heat transfer.
[107] 2021	Fe_3O_4-MWCNT-water $10^3 \le Ra \le 10^6$ $0 \le Ha \le 100$ $0 \le \varphi \le 0.08$ $10^{-5} \le Da \le 10^{-2}$		As Ha changed from 0 to 100, the stream function dropped by 84.78%.
	Experimental / Nanofluid		
[108] 2017	AlN and TiO_2 in mineral oil Ra $>10^6$ wt = 0.01%, 0.1%, 0.5%		Using nanofluids enhancing h.

4. THE GOVERNING EQUATIONS

The numerical solutions in the field of 3D natural convection inside different cavity geometries, using a set of equations in steady or unsteady situations according to the researcher study assumptions. Which included the continuity, momentum and energy equations to control the fluid inside the cavity. In this work, the unsteady form of the governing equations will be introduced for the classical fluid and nanofluid, respectively.

4.1 The classical fluids governing equations

For classical fluids [59], the continuity equation:

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

The momentum equation in the x-axis:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + v\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

The momentum equation in the y-axis:

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \quad (3)$$

The momentum equation in the z-axis:

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z} =-\frac{1}{\rho}\frac{\partial P}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) + \rho g\beta(T-T_c) \quad (4)$$

The energy equation:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (5)$$

4.2 The nanofluids governing equations

For nanofluids these equations received some modifications due to the solid nanoparticle's addition enhancements. The improved properties include: the density, viscosity and thermal conductivity. Where the governing equations become [79]:

The continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (6)$$

The momentum equation in the x-axis:

$$\rho_{nf}\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right) =-\frac{\partial P}{\partial x}+\mu_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (7)$$

The momentum equation in the y-axis:

$$\rho_{nf}\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right) =-\frac{\partial P}{\partial y}+\mu_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\rho_{nf}g \quad (8)$$

The momentum equation in the z-axis:

$$\rho_{nf}\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right) =-\frac{\partial P}{\partial z}+\mu_{nf}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (9)$$

The energy equation:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (10)$$

where, ρ_{nf}, μ_{nf}, α_{nf} are given by [109]:

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \quad (11)$$

$$\mu_{nf}=\frac{\mu_f}{(1-\varphi)^{2.5}} \quad (12)$$

$$\alpha_{nf}=\frac{k_{nf}}{(\rho C_p)_{nf}} \quad (13)$$

$$(\rho C_p)_{nf}=(1-\varphi)(\rho C_p)_f+\varphi(\rho C_p)_s \quad (14)$$

The suggested model of (k_{nf}) for suspensions proposed firstly by Maxwell [110] as:

$$\frac{k_{nf}}{k_f}=1+\frac{3\left(\frac{k_s}{k_f}-1\right)\varphi}{\left(\frac{k_s}{k_f}+2\right)-\left(\frac{k_s}{k_f}-1\right)\varphi} \quad (15)$$

The theory of Maxwell was later improved by Hamilton and Crosser [111] to include the effect of particle shape. These models are essentially some kinds of weighted average of solid and liquid conductivities:

$$\frac{k_{nf}}{k_f}=\frac{k_s+(n-1)k_f-(n-1)\varphi(k_f-k_s)}{k_s+(n-1)k_f+\varphi(k_f-k_s)} \quad (16)$$

where, (n) is the shape factor which is (3) for sphere and (6) for cylinder. Also, it can be approximated for spherical nanoparticles by the Maxwell-Garnetts [110] model as:

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+\varphi(k_f-k_s)} \quad (17)$$

A few higher-order models are also available which try to incorporate particle interactions by incorporating the higher-order terms such as these given by Jeffrey [112]:

$$\frac{k_{nf}}{k_f}=1+3\beta\varphi+\left(3\beta^2+\frac{3\beta^2}{4}+\frac{9\beta^3}{16}\frac{\alpha+2}{2\alpha+3}+\cdots\right)\varphi^2 \quad (18)$$

where:

$$\beta=\frac{\left(\frac{k_s}{k_f}-1\right)}{\left(\frac{k_s}{k_f}+2\right)} \quad (19)$$

And the model of Davis [113] as:

$$\frac{k_{nf}}{k_f}=1+\frac{3\left(\frac{k_s}{k_f}-1\right)}{\left(\frac{k_s}{k_f}+2\right)-\left(\frac{k_s}{k_f}-1\right)\varphi}\left[\varphi+f\left(\frac{k_s}{k_f}\right)\varphi^2+O(\varphi^3)\right] \quad (20)$$

where: $f(10)=2.5$ and $f(8)=0.5$.

5. CONCLUSIONS

This paper presents specific review for the research area of the three-dimensional laminar natural convection inside different regular geometry cavities for the last recent years. The laminar (Ra) was ranging around ($10^3 \leq Ra \leq 10^6$) for classical or nanofluid working fluids in numerical and experimental researches. The main conclusions can be summarized as that:

(1) The theoretical researches on the complex geometry cavities field were very poor.

(2) There is clear gap in the experimental researches in both classical or complex geometry cavities.

(3) It is agreed that for a specified range of the nanoparticle solid volume fraction the heat transferred by natural convection inside cavities enhanced by adding more

nanoparticles. But this behavior became inverse when applying enough external magnetic field.

(4) The inclination angle of the magnetic field also effects the heat transferred inside the cavity.

(5) Multi modifications were applied to the cavity to enhance the heat transferred through it, either using different inclinations for the cavity.

(6) Changing the heating and cooling system type and location also one of these modifications.

(7) Inserting partitions or fins of different materials solid or porous with different places and inclinations, also enhances the heat transferred.

(8) As like as changing the (AR) of the cavity, dimensions and else was used widely in researches.

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NOMENCLATURE

Be	Bejan number
C_p	specific heat at constant pressure, J.Kg^{-1}. K
c	location of the partition, m
g	acceleration duo to gravity, m.s^{-2}
Ha	Hartmann number
h	height of partition, m
K	thermal conductivity, W.m^{-1}. K^{-1}
Ma	Marangoni number
Nu	Nusselt number
P	pressure, N.m^{-2}
Pr	Prandtl number
Ra	Rayleigh number
T	temperature, k
t	time, s
u	the velocity component in x-direction, m.s^{-1}
v	the velocity component in y-direction, m.s^{-1}
w	the velocity component in z-direction, m.s^{-1}
x	the coordinate in horizontal direction, m
y	the coordinate in vertical direction, m
z	the coordinate in axial direction, m

Greek symbols

α	thermal diffusivity, m^2. s-^{1}
β	coefficient of thermal expansion, K^{-1}
γ	inclination angle of the magnetic field, º
θ	Lorentz force
μ	dynamic viscosity, kg. m^{-1}. s^{-1}
ρ	density, kg.m^{-3}
φ	nanoparticles solid volume fraction
ϴ	inclination angle of the cavity, º
ϕ	inclination angle of the partition, º

Subscripts

b	block
c	cold
D	position of the hot source
E	external
eff	effective
f	fluid
I	internal
L	length
nf	nanofluid
s	solid particle