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A Comprehensive Review of Transient Natural Convection Flow in Enclosures

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ABSTRACT

Various published researches in transient natural convection heat transfer in rectangular or square enclosures are reviewed and described in detail in this comprehensive review by describing the experimental and numerical approaches adopted in studies of this problem in the literature started from the past decade until the recent years. Different thermal boundary conditions for the evolution of the flow regimes and thermal fields of this problem are considered. This review summarizes also recent researches on fluid flow and heat transfer characteristics of three-dimensional effects of transient natural convection and identifies opportunities for future research.
KEYWORDS: Natural convection**,** Transient, Literature review, Enclosure, Laminar flow

1.INTRODUCTION

Transient, time-dependent or unsteady laminar natural convection flows occur in many technological and industrial applications such as in nuclear reactors, rapid cooling process, motion of fluid in computer equipments, radiators, storage devices, cooling of electronic equipment inside computers, furnaces, the growth of crystals for semiconductor industry etc.. In the natural convection process, the buoyancy forces appear due to density variation and this can affect the heat transfer mechanism. Therefore, it is significant to understand the heat transfer characteristics of natural convection in an enclosure or cavity. The transient response of a fluid towards the steady state via a transient natural convection flow has been extensively examined in the literatures under a variety of theoretical, numerical, experimental methods and boundary conditions. The idealized problem of steady laminar natural convection in an enclosure with different boundary conditions has been extensively studied in various works. Recently, in many of the fields of application listed above, the convective flows may be in a transient or unsteady state in an enclosure. Recognizing this fact, much attention has been focused to study the nature of the flow in the transient regime and the manner in which this flow evolves into the final steady state. To author's knowledge, no review paper has been published in the literature up to date related with transient laminar natural convection flows. For this reason, this paper is devoted to help the researches to summarize most published papers in the transient laminar natural convection flows in enclosures and gives them an excellent overview to develop and extend these published papers. We think that this review paper is very necessary to the heat transfer community. The reviewed papers are grouped into various categories in order to be useful for both researches and readers and arranged in each category according to the time of publication to give a coherent overview about the research development in each specific category.

2. LITERATURE REVIEW CATEGORIES

2.1 According to the numerical scheme

Szekely and **Todd [1]** presented an analysis for transient laminar natural convection in a rectangular cavity containing either one fluid or two immiscible liquids. The resultant differential equations were integrated numerically and computed results were presented for the transient streamline patterns and isotherms, for a variety of conditions including high, low and intermediate values of the Prandtl number. **Nicolette et al. [2]** performed a numerical and experimental investigation into two-dimensional transient natural convection of single-phase fluids inside a completely filled square enclosure with one vertical wall cooled and the other three walls insulated. A fully transient semi-implicit upwind differencing scheme with a global pressure correction had been used for the numerical simulation of air and water over the range of $10^5 < Gr < 10^7$. Good agreement was found between the experimental data and numerical predictions. **Khalilolahi** and **Sammakia [3]** used the simple arbitrary Langrangian-Eulerian technique to analyze the

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full two-dimensional equations for unsteady buoyancy-induced flow generated by an isothermal vertical surface enclosed in a long rectangular cavity. They observed the quasi- one-dimensional conduction regime adjacent to the surface at very short times, the steady boundary-layer flow near a semi-infinite surface in an infinite media at intermediate times, and at later times, stratification of temperature field as flow approached its eventual quiescence. **Hadjisophocleous et al. [4]** used a finite-difference method in boundary-fitted non-orthogonal general curvilinear coordinates for the prediction of transient free convection in enclosures of arbitrary geometry. A problem of transient cooling of a square cavity was considered in order to determine the effect of time step and under-relaxation coefficient on the accuracy and efficiency of the solution technique. **Karyakin [5]** considered two-dimensional unsteady natural convection in enclosures of arbitrary cross section. The convection equations in the Boussinesq approximation were written in a curvilinear non-orthogonal coordinate system, in which the boundaries of the region investigated coincided with the coordinate lines. The problem was solved numerically in the physical variables on the basis of a multi-step, completely implicit finite-difference method with decoupling of the physical processes and space variables. **Le Quéré [6]** presented a note on multiple and unsteady solutions in a two-dimensional convection in a tall cavity to understand the effect of convection induced flow patterns on the heat transfer. **Sai et al. [7]** presented solutions for the transient problem in the Rayleigh number range of 10^3-10^6 by the application of the finite element method based on the first-order projection scheme, which was an extension of Chorin's algorithm. **Nobile [8]** performed a numerical simulation of time-dependent flow in cavities with the correction multigrid method. **Nithiarasu et al. [9]** employed using the Galerkin's finite element coupled with Eulerian velocity correction scheme for pressure prediction the transient natural convective flow and heat transfer in a combined vertical and horizontal enclosure. A detailed parametric study had been undertaken for evaluating the effects of Rayleigh number, width ratio and prescribed boundary conditions. The results indicated that the flow and isothermal patterns were strongly dependent on Rayleigh number and width ratio. **Machado et al. [10]** presented a flexible algorithm for transient thermal convection problems via integral transforms. **Leal et al. [11]** investigated transient natural convection in enclosures with variable fluid properties by integral transform solutions for different values of the Rayleigh number, from 10^3 to 10^5 and Prandtl number equals to 0.71. They concluded that, the properties variation effects were considerable well within the assumed region of applicability for the Boussinesq simplification. **Guo** and **Bathe [12]** had been obtained the solutions of a benchmark problem of cavity unsteady flow near the critical Rayleigh number using the ADINA system. The flow patterns including the boundary layers and vortices were also studied based on the results obtained with the finest mesh of (40×120) 9-node elements. Periodic solutions with a period of (3.42–3.43) were obtained in all simulations. Compared with the averages of the various solution variables and the periods, the amplitudes of the periodic solutions were more sensitive to the spatial and temporal discretizations used. **Christon et al. [13]** performed a computational predictability with a benchmark solution of time-dependent natural convection flows in enclosures. **Bubnovich et al. [14]** applied an implicit scheme to the solution by finite differences of transient natural convection in terms of the stream function and temperature. The second-order energy differential and fourth-order momentum equations were discretized according to the well-known alternate direction implicit (ADI) method. The transient solution to the problem was presented using the average and local Nusselt numbers on the hot wall. Both the transient and permanent solution results were compared with the results of five another published studies.**Ha et al. [15]** obtained a two-dimensional solution for unsteady natural convection in an enclosure with a square body using an accurate Chevyshev spectral collocation method. The considered physical model was a square body located at the center between the bottom hot and top cold walls. When the Rayleigh number was small, the flow and temperature fields between the hot and cold walls showed a symmetrical and steady pattern. While, when the Rayleigh number was high, the flow and temperature fields became time-dependent, and their time-averaged shapes approached the symmetric pattern. **Vynnycky** and **Kimura [16]** considered both analytically and numerically the transient process of the solidification of a pure liquid phase-change material in the presence of natural convection in a rectangular enclosure. One vertical boundary was held at a temperature below the melting point of the material, the other above; while the horizontal boundaries were both assumed adiabatic. A non-dimensional analysis of the problem, principally in terms of the Rayleigh (Ra) and Stefan (St) numbers, indicated that some asymptotic simplification was possible for materials often considered in the literature (water, gallium, lauric acid). **Ben Cheikh et al. [17]** investigated a two-dimensional numerical study of transient natural convection flow in an air filled enclosure of aspect ratio (A = 9). The numerical method was based on a second order finite volume scheme and a projection method. The multi-grid procedure was briefly described and the critical Rayleigh number above which the flow became unsteady was determined. **Ben Cheikh et al. [18]** presented a benchmark solution for time-dependent natural convection flows with an accelerated full-multigrid method.

2.2 Differentially heated enclosures.

Patterson and **Imberger [19]** studied unsteady natural convection in a rectangular cavity with instantaneous cooling and heating of two opposite vertical sidewalls. They concluded that the flow had a strong dependence on the Prandtl number and cavity aspect ratio. **LeQuere** and **De Roquefort [20]** investigated the transition process to unsteady natural convection of air in a differentially heated vertical cavities. **Kuhn** and **Oosthuizen [21]** performed a numerical analysis on transient natural convective flow in a rectangular enclosure with a uniformly heated vertical wall. **Schladow et al. [22]** conducted a series of two and three-dimensional numerical simulations of the transient flow in a side-heated cavity. Their simulations generally agreed with the results of the scaling arguments of **Patterson** and **Imberger**

[19].**Hyun** and **Lee [23]** investigated numerically the two-dimensional transient natural convection heat transfer in a square cavity, where the opposing sidewalls were subjected to an arbitrary time variations in temperature. **Patterson** and **Armfield [24]** presented comparisons of numerical and experimental results for transient two-dimensional natural convection initiated by instantaneously heating and cooling the opposing vertical walls of a square cavity containing a stationary and isothermal fluid. **Oosthuizen** and **Paul [25]** investigated numerically unsteady free convective flow in an enclosure containing water near its density maximum. **Mahdi** and **Kinney [26]** used a finite volume approach with adaptive upwind convection to predict the two-dimensional unsteady flow in a square cavity filled with air. The natural convection was induced by differentially heated vertical walls. Image vorticity was used to enforce the zero-penetration condition at the cavity walls. Unsteady predictions were carried sufficiently forward in time to reach a steady state. The steady state predictions were compared with published results obtained using a finite difference scheme for the same values of Prandtl and Rayleigh numbers. **Lin et al. [27]** investigated transient binary mixture natural convection in square enclosures. **Schladow [28]** analyzed numerically the fluid oscillation motion in a side-heated cavity and found the presence of both long-period and short-period oscillations. He explained that natural convection of the transient flow structure was so complex that it needed more research attention. **Mohamad** and **Viskanta [29]** analyzed the transient convective motion in a two-dimensional square cavity driven by a temperature gradient. The cavity was filled with a low-Prandtl number fluid and the vertical walls were maintained at constant but different temperatures, while the horizontal boundaries were considered adiabatic. Numerical solutions were obtained for Prandtl numbers of 0·001, 0·005 and 0·01 and for Grashof numbers up to 1×10^7. It was found that the flow field exhibited a periodic oscillation at the critical Grashof numbers, which were dependent on the Prandtl number. **Kazmierczak et al. [30]** investigated the effect of the oscillating surface temperature on the buoyancy driven flow and heat transfer in an enclosure with time periodic boundary conditions. **Peltier** and **Biringen [31]** presented a numerical simulation of transient thermal-convective mechanism for oscillatory thermocapillary convection in a shallow rectangular cavity for a fluid with Prandtl number of **6.78**. The results explained the development of a stability diagram presenting the critical Marangoni number separating the steady from the time-dependent flow states as a function of aspect ratio for the range of values between **2.3** and **3.8. Oosthuizen** and **Paul [32]** numerically studied unsteady natural convective flow in an enclosure with a periodically varying side wall temperature. **Moh et al. [33]** simulated numerically the two-dimensional, low Prandtl number natural convection in harmonically oscillated, differentially heated square enclosures. Average heat transfer rates were correlated for liquids with Pr = 0.02 and 0.03.**Bellahmar** and **Maslouhi [34]** investigated numerically unsteady natural convection with viscosity variation in two-dimensional square enclosure. **Kumar et al. [35]** performed a numerical study to analyze the characteristics of transition from laminar to chaotic natural connection in a fluid-filled two-dimensional, unity aspect ratio rectangular cavity with mixed thermal boundary conditions. They found that as Rayleigh number increased, various measures of chaos, such as power spectrum, phase portrait, and time series of various dynamical variable signals was observed. **Aydin [36]** studied transient natural convection in rectangular enclosures heated from bottom and cooled from above. **Abourida et al. [37]** investigated by a finite difference procedure natural convection in a square cavity with its horizontal walls submitted to different heating models. The hot temperature of the bottom surface varied sinusoidally with time, while that of the opposite surface (cold temperature) was maintained constant or varied sinusoidally. The vertical walls were considered adiabatic. The results obtained showed that the heat transfer could be enhanced or reduced, with respect to the case of constant temperatures, by proper choice of the variable heating mode. **Sammouda et al. [38]** used the finite element method to simulate the transient natural convection of low-Prandtl number fluids in a heated cavity. **Bellahmar** and **Maslouhi [39]** investigated numerically using an alternate implicit finite difference (ADI) method the steady and transient laminar two-dimensional natural convection of a Newtonian fluid with variable properties in a square cavity with differentially heated end walls. The temperature-dependent viscosity effect was studied. The characteristic transient velocity and temperature increased to a peak and decreased to a steady value. This overshoot phenomenon was amplified or attenuated depending on the values selected for the dimensionless parameters characterizing the viscosity variation. **Bennacer et al. [40]** investigated numerically and analytically the transient double diffusive natural convection in a horizontal enclosure with horizontal temperature and vertical solutal gradients. It had been found for lower buoyancy ratio value the convective cell was essentially due to thermal forces while for high buoyancy ratio value the transfer was diffusive. **Christon et al. [41]** performed a numerical study to determine the most accurate estimate of the critical Rayleigh number above which the flow was unsteady and the best time-dependent benchmark solution for the 8:1 differentially heated cavity. They referred that the first critical Rayleigh number provided a transition from steady to a time-dependent flow at $Ra_{crit}=3.0619\times10^5$, while the second critical Rayleigh number made the transition to a time-dependent skew-symmetric flow at $Ra_{crit}=3.1117\times10^5$. **Das et al. [42]** performed an experimental and numerical studies for transient and steady natural convection phenomena in a two-dimensional cavity heated symmetrically from both sides with a uniform heat flux. The flow pattern in the cavity was found to be significantly different from the well-studied phenomena of differentially heated enclosures. The measured temperatures and flow visualization results showed a good agreement with the numerically generated results. **Guo** and **Bathe [43]** presented a solution using the ADINA system of a benchmark problem of natural convection flow in a differentially heated cavity with $Ra=3.4\times10^5$ and Pr = 0.71 .Periodic solutions with a period of 3.42–3.43 were obtained. The flow patterns, such as boundary layers, vortices were also studied using a fine (40×120) element mesh. **Kim** and **Hyun [44]** considered transient buoyant convection in a rectangular cavity. The vertical side walls were at two different temperatures, and the horizontal end walls were thermally insulated. At the initial state, the fluid was motionless and under zero gravity, and a conduction-controlled, horizontally linear temperature profile exists. They observed that the peak value of the Nusselt number was larger than that of the conventional heat-up model. **Crunkleton et al. [45]** made a numerical simulation of periodic flow oscillation for low Prandtl number fluids in rectangular enclosure. They observed non-periodic flows for rectangular cavity with aspect ratio of 2.0. **Nithyadevi et al. [46]** carried out a numerical study of transient natural convection in a square cavity with partly thermally active sidewalls. The thermally active regions of the sidewalls are considered periodic in time. Top and bottom of the cavity were adiabatic. Nine different positions of the thermally active zones were considered. The results were obtained for various values of amplitude, period, and Grashof numbers ranging from 10^4–10^6 and different thermally active situations. They concluded that the average Nusselt number behaved non-linearly as a function of period. **Ridouane et al. [47]** studied numerically coupled laminar natural convection with radiation at steady and unsteady conditions in an air-filled square enclosure heated from below and cooled from above for a wide variety of radiative boundary conditions at the sidewalls. The oscillatory behavior, characterizing the unsteady-state solutions during the transitions from bicellular flows to the unicellular flow were observed and discussed. **Kizildag et al. [48]** presented a numerical predictions regarding unsteady natural convection for water (Pr = 3.77) in a rectangular cavity of 7:1 aspect ratio under transient boundary conditions. The results were obtained for three different variable Rayleigh numbers sets whose maximum values were 1.58 x 10^5, 1.58 x 10^8, and 1.58 x 10^{11} respectively. **Rostami [49]** investigated numerically using finite-volume method unsteady heat transfer and fluid flow characteristics in an enclosure. The enclosure consists of two vertical wavy and two horizontal straight walls. The top and the bottom walls were considered adiabatic. Two wavy walls were kept isothermal and their boundaries were approximated by a cosine function. Simulation was carried out for a range of Grashof number (Gr = 10^3–10^6), Prandtl number (Pr = 0.5–4.0), wave ratio (0.0–0.35) and aspect ratio (0.5–1.0). The obtained results were in good agreement with available numerical and experimental data. **Ouertatani et al. [50]** presented a two-dimensional numerical solutions related to transient natural convection in a square enclosure heated from below and cooled from above. The fluid under consideration was air and the Rayleigh number was taken in the range from 10^3 to 10^6. Benchmark solutions were proposed for the considered range of Rayleigh numbers. **Rangaswamy** and **Natarajan [51]** studied numerically transient natural convective flow in a closed square cavity with adiabatic top and bottom walls. Vertical walls of the cavity were assumed to be partially heated and cooled such that heated and cooled portions face each other in an opposed manner. Three different cases with equal and unequal lengths of hot and cold portions on the vertical walls were considered. Results were obtained for different values of Grashof number and fixed Prandtl number (Pr = 0.733). Average Nusselt number was found to behave as a non-linear function of Grashof number. **Alloui** and **Vasseur [52]** reported an analytical and numerical study of unsteady natural convection in a shallow rectangular cavity filled with a micropolar fluid. Neumann boundary conditions for temperature were applied to the horizontal walls of the enclosure, while the two vertical ones were assumed insulated. The results were obtained from the analytical model for finite-amplitude convection for which the flow and heat transfer were presented in terms of the governing parameters of the problem. **Younis et al. [53]** presented a numerical analysis of the effects of thermal boundary conditions, fluid variable viscosity and wall conduction on transient laminar natural convection of a high Prandtl number fluid (Pr = 4×10^4) in a cubical cavity. The cavity was initially full of fluid at rest and at constant temperature (T_i = 45°C) higher than the temperature of the walls (T_w =25°C). The time evolution of the flow patterns, the temperature contours, the mean temperature of the fluid and the Nusselt number of eight different cases of cooling were presented and analyzed.

2.3 Three-dimensional enclosures.

Kuhn and **Oosthuizen [54-55]** numerically studied transient three-dimensional natural convective flow in a rectangular enclosure. **Kuhn** and **Oosthuizen [56]** investigated numerically three-dimensional transient natural convective flow in a rectangular enclosure with localized heating. **Kuhn** and **Oosthuizen [57-58]** performed a numerical investigation on transient three-dimensional natural convective flow in a rectangular enclosure with two heated elements and a hot spot on a vertical wall respectively. **Fusegi** and **Hyun [59]** investigated a laminar and transitional natural convection in a rectangular enclosure with complex and realistic conditions. Four topical issues were considered which were the finiteness of thermal conductance of the solid walls, the variable physical properties of the fluid, time-dependent thermal loading on the surface walls, and the three-dimensionalities. Discrepancies between the conventional two-dimensional numerical predictions with idealized boundary conditions and the available experimental measurements were highlighted. **Oosthuizen [60]** investigated numerically the three-dimensional, unsteady natural convection in a partially heated horizontal enclosure. **Oosthuizen** and **Paul [61]** numerically studied three-dimensional, unsteady natural convection in a horizontal enclosure with a heated strip on the lower surface and cooled side and top surfaces. **Nelson** and **Sylvana [62]** investigated using finite-volume method the three-dimensional unsteady natural convection of cooling water inside a cubical cavity at Ra = 10^5. All physical water properties were considered to change with temperature. The numerical results for the 3-D geometry showed that the side effects were relevant in fluid mechanics and in heat transfer, with larger differences than with the 2-D predictions in the region where the density anomaly of water was important. **Oosthuizen** and **Paul [63]** investigated numerically the effect of wall thermal boundary conditions on the development of three-dimensional, unsteady natural convective flow in a horizontal enclosure with a heated strip on the lower surface. **Oosthuizen** and **Paul [64]** numerically studied the three-dimensional unsteady natural convective flow in a rectangular enclosure. The enclosure had a rectangular horizontal lower and upper surfaces and vertical side surfaces. The horizontal width of the enclosure was twice the vertical height of it while the longitudinal length of the enclosure was equal to the vertical height of it. Three square, symmetrically isothermal heated sections was placed on the lower surface while the rest of this surface being adiabatic. The variation of average Nusselt number with Rayleigh number and the effect of unsteadiness in the flow had been investigated. **Kurtbas** and **Durmus [65]** solved numerically three-dimensional unsteady state equations of flow and heat transfer by natural convection in the cavity of a passive heating room. Variable heat flux boundary condition depending on time was applied on the absorber surface using values of hourly averaged radiation. Convection boundary condition was used on glass surface, the walls and ceiling of the room by using overall heat transfer coefficient. They concluded that the overall heat transfer coefficient for low Rayleigh number affected the average Nusselt number more than that of high Rayleigh number. **Sedelnikov et al. [66]** performed a three-dimensional numerical study of transient natural convection in a cubical cavity heated from below and rotating about its vertical axis of symmetry in the case when the two horizontal boundaries were isothermal while the four vertical walls were insulated. They concluded that the onset of convection always occurred in an oscillatory manner leading to waves propagating in the retrograde direction (with respect to the sense of rotation) along the side walls.

2.4 Enclosures with localized heating and internal heat generation.

Kuhn and **Oosthuizen [67]** numerically studied transient natural convective flow in a rectangular enclosure with localized heating on a vertical wall. **Kuhn** and **Oosthuizen [68]** performed a numerical study on unsteady natural convection in a partially heated rectangular cavity. They concluded that as the heated location moved from the top to the bottom, the Nusselt number increased up to a maximum value and then decreased. **Lee** and **Hyun [69]** investigated a time-dependent double diffusive convection in a stable stratified fluid under lateral heating. **Poujol et al. [70]** numerically studied the transient natural convection of a fluid with a Prandtl number of order 200 in a two-dimensional square cavity. One of the vertical walls of the cavity was kept at a constant (ambient) temperature and a constant heat flux was applied on the opposite wall. The other walls were adiabatic .They observed that as time progressed, the average temperature in the cavity increased, and a descending boundary layer was formed near the constant temperature wall. **Oosthuizen** and **Paul [71]** investigated numerically unsteady natural convective flow in an enclosure with a heated sidewall having a periodically varying heat flux. **Baytas [72]** carried out a computational study to investigate the effect of the sinusoidally driven heat source on the fluid flow and heat transfer within a two-dimensional square cavity. The cavity, which had solid walls of constant temperature, was filled with a fluid including uniformly distributed internal heat source. The effects of the different periods of the sinusoidally driving heat source on heat transfer were investigated. **Oosthuizen** and **Paul [73]** simulated numerically unsteady natural convective flow in an enclosure with a periodically varying side wall heat flux. **Shim** and **Hyun [74]** analyzed numerically the time-dependent adjustment of natural convection in a square cavity with internal heat generation. They observed that when the impact of internal heat generation was dominant, the flow adjustment was achieved over the time. **Lakhal et al. [75]** studied the transient natural convection in a square cavity partially heated from side. They noticed that the temperature was varied sinusoidally with time .The results showed that the mean values of heat transfer and flow intensity were considerably different with those obtained in stationary regime. **Ha et al. [76]** performed a numerical study on transient heat transfer and fluid flow of natural convection in an enclosure with a heat-generating conducting body. **Bellahmar** and **Maslouhi [77]** numerically studied transient natural convection with viscosity variation in an enclosure with localized heating. **Kim et al. [78]** studied the buoyant convection with internal heat generation under oscillating sidewall temperature of a cavity. It was found that the secondary peak resonance was detected for higher internal Rayleigh number. **Prudhomme et al. [79]** studied unsteady free convection in a vertical cavity heated from the four walls by uniform heat fluxes. Analytical solutions were derived for a fully developed base flow. They observed that a Hopf type bifurcation occurred at the critical Rayleigh number, over the entire considered range of Prandtl numbers and heat flux ratios. They predicted instability modes depending on the value of the Prandtl number, either thermal, for $Pr > 1$, or hydrodynamic, for $Pr < 1$. **Bae** and **Hyun [80]** carried out a numerical study of the transient convection in rectangular and elongated cavities with a hot wall composed by three heated bands. They presented the temperature evolution of the three heaters for Rayleigh number in the range 10^5–10^7 and the analysis of the inner flow through the streamlines and temperature distribution as a function of the dimensionless time. **Ben Cheikh et al. [81]** studied numerically transient natural convection in air-filled 2D square enclosure heated with a constant source from below and cooled from above for a variety of thermal boundary conditions at the top and sidewalls. Simulations were performed for two kinds of lengths of the heated source, i.e., a small and a large source corresponding to 20% and 80% of the total length of the bottom wall, respectively. The Rayleigh number varied from 10^3 to 10^7. Results were presented in the form of streamline and isotherm plots as well as the variation of the Nusselt number and maximum temperature at the heat source surface.

2.5 Experimental investigations

Bar-Cohen and **Herman [82]** performed an experimental investigation of transient natural convection heat transfer resulting from constant heating of an enclosed fluid for a range of enclosure aspect ratios and heating rates. A tentative correlation of the prevailing Nusselt numbers was presented. **Ivey [83]** performed an experiments on transient natural convection in a cavity and found the oscillations of flow. He referred that flow pattern between the case of low Prandtl number fluid and the case of high Prandtl number fluid was significantly different. **Upton** and **Watt [84]**

performed an experimental study for two-dimensional transient natural convection in an inclined rectangular enclosure. The transient boundary conditions were initiated by heating and cooling two opposing walls. The evolution of the flow to steady-state was determined for a Prandtl number of 6.38, a Rayleigh number of 1.5×10^5 and an aspect ratio of 1.0, at angles of inclination of $\pi/4$, $\pi/2$ and $3\pi/4$. **Bhowmik** and **Tou [85]** performed an experiments using water to study the single-phase transient natural convection heat transfer from in-line four simulated electronic chips, which were flush-mounted to one wall of a vertical rectangular channel. The heat flux ranges from 1 KW/m^2 to 6 KW/m^2. The results indicated that the heat transfer coefficient was affected strongly by the number of chips. Results were compared with those obtained from the literature for steady-state forced and natural convection heat transfer.

2.6 Inclined enclosures

Koutsoheras and **Charters [86]** studied numerically the effects of Rayleigh number, aspect ratio and angle of inclination on the transient natural convection through an inclined air-cell (like an enclosure). This was done for two side wall boundary conditions, namely that of perfectly insulating and infinitely conducting sidewalls. A discussion of the relevance of their work to solar absorbers was included, with the major conclusion being that, depending on the aspect ratio of the cell used, cellular structures could be effective in reducing convective losses in inclined absorbers. **Talaie** and **Chen [87]** numerically studied steady and transient laminar two dimensional natural convection of a fluid in an inclined rectangular enclosure. The effect of inclination angle on the flow development was discussed. **Tzeng et al. [88]** performed a numerical investigation of transient flow mode transition of laminar natural convection of air in an inclined rectangular enclosure. They concluded that the natural convection in an inclined enclosures was very sensitive to the change in tilt angle. **Skouta et al. [89] performed** a numerical investigation of two-dimensional transient convection in an air filled square enclosure which was tilted in relation to the horizontal plane and heated from two opposite sides. **Jeng [90]** performed an experimental and numerical study of steady state and transient natural convection in inclined enclosures. **Ouriemi et al. [91]** reported an analytical and numerical study of the transient natural convection in an inclined shallow cavity filled with a binary fluid. Newmann boundary conditions for temperature were applied to the long side walls of the enclosure, while the two short ones were assumed to be impermeable and insulated. The governing parameters for the problem were the Rayleigh number, the Lewis number, the buoyancy ratio, the inclination of the cavity, the Prandtl number and the cavity aspect ratio. It was demonstrated that, for small enough inclinations around the horizontal plane, multiple steady states exist, some of which were unstable. **Ouriemi et al. [92]** investigated unsteady natural convection of a binary mixture confined in a tall enclosure, slightly inclined about the gravity field. The cavity was heated from the bottom by a constant heat flux while the long side walls were considered impermeable and adiabatic. They demonstrated the existence of multiple steady states, for small enough inclinations around the vertical plane. **AL-Bahi et al. [93]** studied numerically the effect of inclination angle on the transient laminar free convection in a rectangular enclosure with aspect ratio = 5, which was discretely heated by an isoflux flush mounted small heater. The local and average Nusselt numbers were compared at inclination angles from 0° (bottom heating) to 180° (top heating), for modified Rayleigh numbers. The two-dimensional mass, momentum and energy equations were solved with the sidewalls were adiabatic and the heat sink was isothermal. The effect of the orientation angle on the flow structure and associated transition between unicellular and multiple cell flow was presented. **Altac** and **Kurtul [94]** performed a numerical study using the finite volume method of laminar natural convection in tilted rectangular enclosures that contained a vertically situated hot plate. The plate was very thin and isothermal on both lateral ends, and it acted as a heat source within the medium. Three surfaces of the rectangular enclosure were considered insulated while one lateral surface was cold. The Rayleigh numbers and the enclosure tilt angle were ranged from 10^5 to 10^7 and from (0 degree) to (90 degree), respectively. The aspect ratios of the rectangular enclosures were considered as A = 1 and A = 2. The steady state plate surface-averaged Nusselt numbers were computed for each case as a function of Rayleigh number and other non-dimensional geometrical parameters. **Skouta et al. [95]** performed a numerical study involving unsteady natural convection inside an air-filled square cavity, tilted in relation to the horizontal plane (α =30° and 60°), which was heated from two opposite sides and cooled from the other two sides. The behavior of the system with increasing Rayleigh number was analyzed using centered finite-differences. The results explained that the tilt angles had a strong influence on the transition toward chaos. **Jeng et al. [96]** performed both experiments and numerical work to study transient natural convection flow and transport process due to mass transfer in the enclosures inclined at different angles. In the experiments, the enclosure was filled with aqueous solution containing $CuSO_4$ + H_2SO_4 where the flow structure can be visualized by both particle tracer and shadowgraph. Two opposed sidewalls of the enclosure were maintained at different concentrations which were made by passing current through the electrodes at the limiting condition. All the other sidewalls were considered insulated and impermeable to the species transfer. During the experiments, the Rayleigh number ranges from 1.126×10^8 to 1.157×10^{11}, the angles of inclination from 30 to 90 degree and the aspects ratio of the enclosure from 0.6 to 1. **Beya** and **Lili [97]** studied numerically the transient natural convection in 3D cubic tilted enclosure heated from two opposite sides. Simulations had been carried out for Rayleigh numbers ranging from 10^3 to 1.3×10^5, Prandtl number ranging from ($0.71 \leq Pr \leq 75$) and inclination angle ($0° \leq \gamma \leq 90°$). A periodic behavior of the 3D flow had been observed at $Ra = 8.5\times10^4$ with a fundamental frequency of 8.27.

2.7 Enclosures with baffle

Perng and **Shieh [98]** studied numerically transient laminar natural convection in an enclosure partitioned by an adiabatic baffle. **Fu et al. [99]** investigated numerically using finite element method the transient laminar natural convection in an enclosure partitioned by an adiabatic baffle. The enclosure was heated by uniform heat flux from left wall and cooled from right wall at isothermal temperature. The effects of the baffle and Rayleigh number were found to be substantial on heat transfer mechanism during transient process. **Xu et al. [100]** performed a numerical simulations of unsteady natural convection in a differentially heated cavity with a thin fin of different lengths on a sidewall at the Raleigh number of 3.8×10^9. It was found that the fin length significantly influenced on the transient thermal flow around the fin and heat transfer through the finned sidewall in the early stage of the transient flow development.

6. Conclusions

This paper presents a comprehensive literature review of the most published papers in the transient laminar natural convection heat transfer in enclosures. Many important papers in the literature with their conclusions have been described in detail and classified in various sections according to their specification. We think that further numerical and experimental research investigations are needed to understand the heat transfer characteristics of transient laminar natural convection in enclosures and identify new and unique applications for this field.

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