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Geometrical and Thermal Parameters for Integrated Heated Enclosures Design: A Review

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Abstract: *This paper reviews the various geometrical and thermal parameters influencing heat distribution behaviour for integrated enclosure design which extensively studied by past researchers. Selected works on configuration geometrical, wall inner surface, design aspect ratio, baffle arrangement, and heat source inside the heated enclosures are reviewed. The chimney effect, buoyancy effect and heat transfer mode both for natural and forced convection inside heated enclosure are examined. A series of numerical and experimental tests to assess the effect of fluids dynamic parameters with fluids dynamic equations derivations were also investigated. The increasing number of study interests in heat streamlines, heat transfers and fluid flow behaviour prediction were reflected by the increasing concern with attempt to achieve better design for heat uniformity distribution with efficient heat removal. Different perspectives and interest drag the attention of industrialists, engineers and scientists from varying disciplines such as architectural, chemical, environmental, electronics, mechanical, automotive and food technology science. Special attention has been given for physical design factors which affect convective heat transfer behaviours due to its dominant in quick uniformity recovery in heat distribution within temperature-time. Integrating employed methods and techniques presented in thermal management inside enclosures by different point of view could be adapted to cater the challenging issues and extendable for future research. Corresponding with the current trend demands to reduce energy intensity and efficiency, integrated heated enclosure design and strategies expected to grow in line with effort to contribute better environmental and economic impact.*

Keywords: heated enclosures, convective heat transfer, numerical, experimental, adaptive integrated design

1.0 INTRODUCTION

Geometrical and thermal parameters are consistently regarded as one of the engineering challenges in designing heated enclosures which are widely applied in various fields both in engineering and physical problems. The major thermal performance concerned mostly deals with the uniformity in heat distribution and heat dissipation removal. The convection heat transfer mode identified as the most dominant with design issue and has been considered as one of the most important research topics due to its wide range of applications in the engineering and physical problems including heat exchangers, food, solidification, ventilation and electronic cooling [1].

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There has been an increasing interest in the heat streamlines, distributions and fluid flow behaviour prediction studies inside a heated enclosure. Functions and streamlines have been extensively used to visualize two-dimensional fluid, heat and mass transportation structures [2]. Various techniques and approaches have been proposed by researchers which are related to the fluid mechanics, mass and heat transfer via both computational and experimental methods. Dimension of research field become widen by various approach from researchers, both via numerical and experimental methods to achieve uniformity heat distribution inside the enclosure for heated enclosures. Most research findings in the heat flow visualization and internal heat energy distribution inside enclosures are presented by terms of streamlines, heat lines, isotherms, entropy generation due to fluid friction, entropy generation due to heat transfer, total entropy generation and average Nusselt number.

The importance of studies could bring benefit to various fields such as architectural and buildings. Karabay et al. [3] studied relationship between floor heating system and wall heating system to seek the effectiveness in heating. Another works by Liu et al. [4] simulated the slot ventilated enclosure flows, respectively in displacement ventilation and mixed ventilation covering from the forced convection dominated flow to the natural convection dominated flow. Meanwhile, the computer industry sectors reported the trends of increasing heat dissipation in microprocessors and telecommunication cabinets. As a result, thermal management is becoming increasingly critical to the electronic industry, as reported by Zuo et al.[5]. Faster processor generates large amount of heat from inside the limited space of enclosure. Thus, ineffective airflow distribution for heat release mechanisms in enclosure impacting the inside air temperatures which cause thermal and reliability problems. Naphon et al. [6], studied the use of vapour chamber applied on the electronic cooling and concluded that effective thermal spreader can achieve more uniform heat flux distribution and thus enhance heat dissipation of heat sinks.

Extended to the food science, heat distribution was determined as critical and sensitive issue which needs a good heat management system in enclosures for the hot food holding containers. Food technologist and engineers always deal closely with the hot food handling temperature in order to keep food safe as required standard safe hot holding temperature at above 65°Celcius[7]. Several investigations on temperature controlled environment for food safety have been extensively studied by Lamoka et al. [8], Baker and David [9], Garayoa et al. [10] and Doyle et al. [11]. A solid agreement concluded that temperature as a major factor to be controlled to reduce risk of the food borne illness. Temperature control in food delivery system was also carried out by researchers namely: Giacometti and Josic [12], Larsen et al.[13], Li et.al [14], as well as Callaway et al.[15], Amalaradjou and Bhunia [16] and Nissen et al [17] on temperature sensitivity in food handling safety . Conversely, on the heating enclosure component level; the continued growth in food heat dissipation, attendant increase in local heating load and heating airflow requirements, creates challenges for facility heat distribution design, deployment, and operation. The better strategy for improving heating uniformity in the heated enclosure holders for low moisture foods should be applied to eliminate pathogens and reduce the damage to food quality as stressed by Jiao et al. [18] and Kaluri et al.[19].

Since the early design stage appears to become crucial, a comprehensive ventilation strategy is needed in order to promote quicker uniformity in heat distribution by optimizing the efficient utilization of heat from local heating source inside the enclosure. We attempt to review the various dimensions on thermal and geometric parameters which affect thermal distribution performance in the present paper. However, to the best of authors' knowledge, there is no comprehensive literature on the integrated design model developed by the findings studied.

The purpose of this paper is to understand the geometrical and thermal parameters which are the key issues that influenced the heat distribution uniformity and to propose suggestions that could lead to develop new strategies to enhance temperature-time heat distribution inside heated enclosure. Hence, these pressure points will eventually create more niches for better upcoming findings for both design directions, as well as better conservation in heat. It is therefore to these problems that the following chapters are directed.

1.1 Fundamental of Heat Transfers in Enclosures

The heat transferred phenomena inside an enclosure could be clustered as conduction, convection and radiation. However, this review interests is limited on the convective mode since it appears to give significant different influence in creating heat streamline and distribution behaviours in most numerical and experimental enclosure studies. According to Serth et al. [20], the convective heat transfer phenomena occurs when a gas or liquid flows past a solid surface which temperature is different from that of the fluids. Two broad categories of the convective heat transfer were distinguished; namely, forced convection and natural (or free) convection. In forced convection, the fluid motion is caused by an external agent such as a pump or blower, while in natural convection the fluid motion is the result of buoyancy forces created by temperature differences within the fluids.

Achieving uniformity in temperature distribution in a heated enclosure has a very close relationship with several design factors which influenced the thermal distribution behaviours, impacting the rates of heating and recovery time to achieve desired temperature. The stratification arising out of convection may be desirable or undesirable depending on applications. In order to control the degree of stratification, the understanding of flow pattern and temperature profiles is required as stressed by Ganguli et al. [21]. In the following part, we will present some published works with topics arranged thematically based on geometrical and thermal parameters.

1.2 Geometrical Parameters in Heated Enclosure Design

This section intends to encompass the published works related with geometrical based study of heat transfer behaviours, including numerical, analytical and experimental on convective heat transfer problems inside enclosure. Geometrical parameters influence thermal distribution behaviours such as heat lines and entropy generation for the case of convection within enclosures in the presence of local heating with adiabatic wall. Although extensive cannot include every detail, some selections are necessary. The optimization of geometrical parameters and fluid flow rates inside the enclosure significantly influences thermal behaviours of thermal distributions, in order to operate at given setting temperature. Arranged thematically, we present selected geometry and studies based on shape configurations, enclosure aspect ratio, baffles arrangement and wall condition of rectangular, triangular, trapezoidal, cylindrical and concave/convex enclosures.

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1.3 Effect of Geometrical Shape and Configurations

Over the recent years, a good number of published articles have focused on convection due to heating and cooling of side walls, where local thermal non-equilibrium model are adopted. Rectangular shape enclosures are one of the most preferred studied by researchers in different point of interest. Wu et al. [22] worked on rectangular enclosure to investigate the natural convective flow and heat transfer inside cavity when filled with a heat-generating porous medium by adopting the local thermal non-equilibrium model. Enclosure modelled have adiabatic top and bottom walls, with both left and right walls are partially heated and partially cooled by sinusoidal temperature profile.

Several researchers have examined the influence of the cavity inclination on the nature of the heat flow and on the convection transfers. A tilted square enclosures attracted Cianfarini et al. [23] to investigate natural convection in air-filled cavity, with two adjacent walls heated and the two opposite walls cooled. A computational model was used to solve the mass, momentum, and energy transfer governing equations for different Rayleigh number in the range of $10^4 \leqslant Ra \leqslant 10^6$, and of the tilting angle of the cavity in the range $0° \leqslant \gamma \leqslant 360°$.

Wang et.al [24] studied a cubic enclosure filled by the liquid metal LiPb flow to investigate the nature convection of the liquid LiPb, due to thermal diffusion with strong magnetic field in the blanket. Rectangular channel shaped solar collector studied by Gereh [25] to investigate the phenomenon of the laminar flow inside the enclosures. He used the finite volume method such the continuity equation, the Navier-Stokes with the schematic SIMPLE programming and thermal energy equation to solve the problems. His findings revealed that problem was connected with Re, with whenever the number of the boundary layer increases, Re decreases. However, his study did not provide quantitative data on the surface heat for the case of local heating applied according to his configuration assumption contains no source or energy.

Combined heat and moisture transport in an enclosure with free port problems numerically was investigated by Tang et al. [26] using a control volume-based finite difference technique. Based on his numerical results, they concluded that the convective heat and moisture transport patterns along with transport rates on horizontal ports greatly depend on properties of porous medium, while the air exchange rate on vertical port is almost unaffected by the buoyancy ratios for most situations.

Stavrakakis et al. [27] modelled a room as square enclosure to investigate the airflow inside enclosure that contains a heat source using numerical simulation using two turbulence models; the well-known standard k–ε model and the RNG k–ε model. Calculated utilizing the CFD results, their findings revealed that the bi-directional flow existing through the burning-room vent is similarly predicted by both turbulence models; the RNG k–ε model leading to higher, and more accurate predictions of temperature variations within the hot upper layer, at least for the single-room case.

A comprehensive study on natural convection in air filled 2D tilted square cavities is experimentally and numerically studied by Bairi [28]. With the hot and cold walls of the cavity maintained isothermal at temperatures T_h and T_c, respectively and the channel of the cavity is adiabatic, measurements and simulations are performed for various geometrical and thermal configurations. Different values of the Rayleigh number, Ra, and the tilt angle, α, of the cavity, ranged from 10 to 1010 while α varies from 0 to 360° were focused in his work. Analysis made based on several significant conditions, corresponding to vertical active walls (α=0°), hot wall at the bottom (α=90°; Rayleigh–Bénard convection), hot wall at the top and pure conductive mode (α=270°). Finite volume method was used to solve the mass, momentum and energy transfer governing equations the average Nusselt number, Nu¯ through computational 2D model. The calculated convective contribution of the heat exchange within the cavity quantified and compared with the measured value Nu¯m. His findings proposed Nu¯–Ra type correlations as useful for sizing structures based on rectangular type cavities.

Avedessian et al. [29] conducted a numerical study to investigate free convection in a tall vertical enclosure with an internal louvered metal blind. The effects of Rayleigh number, enclosure aspect ratio, and blind geometry on the convective heat transfer were considered. The empirical correlation for the average Nusselt number gained from the numerical model has been validated against the experiment. The findings revealed that the Nusselt number correlation can be combined with a simple one-dimensional model to closely predict the enclosure U-value. Even though both studies appear to be suitable in benchmarking the enclosure design, there are still no adequate data provided when different materials for isotherms wall heating sources were applied as the inside heated enclosure wall.

The triangular shape enclosures also attracted many researchers in the heated enclosure studies. A study conducted by Varol et al. [30] on the problem regarding with steady, laminar, natural convection flow in a porous enclosure divided by a triangular massive partition as a solid adiabatic body which is located to the right and top wall. In their model, bottom and left vertical wall of porous enclosure are isothermally heated and cooled, respectively while remaining wall is adiabatic. Governing equations using Darcy model are solved numerically by the finite-difference method and the Successive under Relaxation (SUR) technique is used to solve linear algebraic equations. The massive partition formed two different enclosures, depends on the dimensions of the triangular body, as triangle and trapezoidal. Flow patterns and temperature distributions results were presented at different aspect ratios of (AR) for AR=0, 0.25, 0.50, 0.75 and Rayleigh numbers (100≤Ra≤1000).

Using an improved scaling analysis and direct numerical simulations, Saha and Suvash [31] investigated the behaviours of the fluid flow and heat transfer inside a triangular enclosure due to instantaneous heating on the inclined walls is investigated. The wall was classified into three distinct stages including a start-up stage, a transitional stage and a steady state stage, which can be clearly identified in the analytical and numerical results to obtain major scaling relations of the velocity, thicknesses, Nusselt number and the flow development time of the natural convection boundary layer.

Andalakshmi et al. [32] used Bejan's heatlines approach to study numerically on heat distribution and thermal mixing under steady laminar natural convective flow inside a right-angled triangular enclosure filled with porous media subjected to various wall boundary conditions. They studied the influence of various thermal boundary conditions and inclination angles (φ) on evaluation of complex heat flow patterns as a function of Darcy numbers (Da) for various regimes of Prandtl (Pr) and Rayleigh (Ra) numbers. Based on their findings, maximum heat transfer occurs at the top vertex for lower top angle (φ=15∘) at higher Da (Da=10–3). When φ increases to 45∘, the maximum heat flux at the top vertex decreases and

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thermal mixing increases irrespective of Da and Pr. They revealed that the enhanced convection at higher Da significantly affects the heat flow distribution, which is clearly depicted by high local Nusselt numbers at Da=10−3. The isothermal heating of walls enhances the heat distribution and thermal mixing with conclusion made that heatlines provide suitable guideline on thermal management in porous right-angled triangular enclosures with various heating strategies.

Through experimental and numerical analysis, Yesiloz et al. [33] investigated natural convection in a right-angled triangular cavity heated from below and cooled on sidewall while its other wall, the hypotenuse, is kept adiabatic. Their intention is focused on enclosure filled with water and heat transfer surfaces are maintained at constant temperature. Using a commercial CFD package, FLUENT, numerical obtained by finite volume method applied to visualized flow involving the use of the particle tracing method. Effects of Rayleigh number, Ra on the Nusselt number, Nu as well as velocity and temperature fields investigated ranged from Ra from 103 to 107. They showed that the experimental and numerical results agree fairly well with a correlation for Nu developed.

Saha et al. [34] conducted a study to investigate transient natural convection in an isosceles triangular enclosure subject to non-uniformly cooling at the inclined surfaces and uniform base heating. Finite Volume Method used in the numerical simulations of the unsteady flows over a range of Rayleigh numbers and aspect ratios. The flow is potentially unstable since the upper inclined surfaces are linearly cooled and the bottom surface is heated. Transient flow development in the enclosure can be classified into three distinct stages classified; an early stage, a transitional stage, and a steady stage. They revealed that governing parameters, Rayleigh number and aspect ratio significantly impacting the flow inside the enclosure. Their findings suggest a pitchfork bifurcation of the flow about the geometric centre line to be analysed and heat transfer through the roof and the ceiling reported as a form of Nusselt numbers.

Natural convection in trapezoidal enclosures was studied by Basak et al. [35]. For uniformly heated bottom wall, linearly heated vertical wall(s) in the presence of insulated top wall have been investigated numerically with penalty finite element method. Parametric studies for the wide range of Rayleigh numbers (Ra=103-105) and Prandtl numbers (Pr=0.7-1000) with various tilt angles of side walls (φ) have been performed. For linearly heated side walls, symmetry in flow pattern was observed. Secondary circulations observed near the bottom wall for φ=0° for larger Pr (Pr⩾0.7). In contrast, for linearly heated left wall and cooled right wall, the secondary circulations are stronger near the top portion of the left wall especially for larger Pr. The strength of convection is larger for φ=45° and flow intensities are found to be larger for higher Prandtl numbers. Local heat transfer rates are found to be relatively larger for φ=0°. Average Nusselt number plots show higher heat transfer rates for φ=0° and the overall heat transfer rates at the bottom wall is larger for the linearly heated left wall and cooled right wall.

Entropy generation analysis during natural convection in a porous trapezoidal structures of various inclination angles (φ) with two condition isothermal and non-isothermal hot bottom wall has been studied by Basak et al [36]. Simulations have been done to obtain solutions in terms of isotherms (θ), stream function (ψ) and entropy generation maps (Sθ and Sψ) for various ranges of modified Darcy number (Da), Prandtl number (Pr) at modified Rayleigh number, Ra=106. They observed that Sθ, max occurs near the bottom corners for case 1 whereas case 2 occurs near the middle part of the left and right portions of the bottom wall.

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The entropy production due to fluid flow irreversibility (Sψ,max) occurs either at the top wall, or side walls or along the interface between two counter-rotating cells. It is found that, square cavities may be the optimal geometry in comparison to trapezoidal cavities for both cases. Also, trapezoidal cavities with φ=60° may be the alternative optimal design in comparison with φ=45° for all Pr fluids.

Thermal management via distributions of heatlines and entropy generation for natural convection within trapezoidal cavities in the presence of hot left wall, cold right wall and adiabatic horizontal walls has been studied by Ramakrishna et al. [1]. Heat flow visualization has been carried out via the heatline concept. Galerkin finite element method has been used to analyse streamlines, isotherms, heatlines, entropy generation due to fluid friction and heat transfer over the wide range of parameters ($10^{-5} \leq Da \leq 10^{-3}$; 0:015 ≤ Pr ≤1000 at Ra = 106). At low Darcy number ($Da = 10^{-5}$), conduction dominant heat transfer is found based on low magnitudes of streamlines and heatlines. Battachar et al. [37] analysed the probable steady state flow structures and temperature patterns that may evolve during the mixed convection within a lid-driven trapezoidal enclosure with cold top wall and hot bottom wall as the speed of moving lid varies with respect to the intensity of imposed temperature gradients. Grashof number varied from 103 to 105 at Re=1 and 100 for three different fluids of Pr=0.015, 0.7 and 10. Simulations performed for two different scenarios of isothermal (case 1) and non-isothermal (case 2) bottom wall with 45° inclination angle of the side wall. Through findings, non-isothermal bottom wall (case 2) leads to multiple steady states in either natural convection dominated regime (Gr/Re2≫1) or mixed convection regime (Gr/Re2~O(1)) in convection dominated heat transport regime (Pr×Re≳1). Number of steady states are observed to be more in natural convection dominated regime at Re=1. The flow structures of various steady states are found to be crucial to achieve higher heat transfer rates for non-isothermal bottom wall.

Nature of design varies with the space and needs. Beside rectangular or cubic shape enclosures, there are several geometrical shapes which are almost found in the practices. Cylindrical shape enclosure being studied by Costa et al. [38] to investigate uniformity in water temperature and concentration distributions. They reported that wall temperature decreases with time leads to some water condensation at the walls, and wall temperature increases with time leads to evaporation of some liquid water from the walls if it exists there. Ganguli et al. [21] used Computational Fluid Dynamic (CFD) simulations in order to control the degree of stratification. In their work, transient natural convection in a cylindrical enclosure has been investigated for water with CFD simulations and flow visualization [using particle image velocimetry (PIV) and hot film anemometry (HFA)] over a wide range of parameters namely Rayleigh number (1.08×1011≤Ra≤3.76×1013) and aspect ratio (1≤H/R≤2). The effect of various parameters like pressure, tube diameter and aspect ratio on the extent of stratification has been studied.

Computational study of natural convection within differentially heated enclosures with curved (concave/convex) side walls is carried out by Biswal et al. [39]. Via entropy generation analysis, a numerical simulation for various Prandtl numbers (Pr=0.015 and 1000) and Rayleigh numbers (103⩽Ra⩽105) with different wall curvatures tested. Results obtained in their work presented in terms of isotherms (θ), streamlines (ψ), entropy generation due to heat transfer (Sθ) and fluid friction (Sψ). Research findings also revealed that the enclosure in concave with high concavity was chosen as the energy efficient case at high Ra and high Pr.

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From the selected studies on geometrical shape which previously reviewed, the information regarding to the thermal parameters concerned of each shape could be used as justification applied in designing heated enclosure for enhancing thermal management to meet specific design requirements. At present, various findings from researchers in different shapes have a potential to be blended as strategies to design heated enclosure However, based on the result obtained from both numerical and experimental, there is less attention given in investigating the integrated shape for heated enclosure design. Most of the reviewed analysis studies focus on single shape enclosure and still lack of diversity in hybrid shape configurations. Some studies provided quantitative and graphical data in dimensionless parameters range with variation of enclosures configurations angle. However, it is quite different when the enclosures are in movement or under continuous vibration impact. In the next chapter, we extend our review of some other findings from researchers who are directly relevant to the design considerations, as major concern for enhanced heat distribution.

1.4 Effects of Enclosure Aspect Ratio

Some researchers highlighted enclosure ratio as subject matter in effort to enhance convection inside enclosures. Mahapatra et al. [40] considered six different configurations with enclosure aspect ratios 1.5, 2 and 4 as subject matters in research of natural convection in a partially heated enclosure in order to identify the optimum location of the active wall for better heat transfer, in consideration with entropy generation. They finally concluded that different sets of active wall locations varying heat transfer, thermal mixing and temperature uniformity for Rayleigh number 103–106 and Prandtl number 0.71. Detailed from Cheong et al. [41], the heat transfer increases first then decreases with the increasing in the inclination of the enclosure for all aspects of ratio and Rayleigh number. Increasing the aspect ratio shows a decreasing trend of the heat transfer for all Rayleigh numbers considered.

Quelati et al. [42] studied the double-diffusive natural convection with entropy generation in a two-dimensional enclosure with partial vertical heating and salting sources for an aspect ratio Ar=4 A numerical methodology based on the finite volume method and a full multigrid technique employed to observe the effects of parameters. Numerical investigation performed by Ramakrishna et al. [43] for mixed convection heat transfer within square cavities for various thermal boundary conditions on bottom and side walls were based on thermal aspect ratio (A). They used a penalty finite element analysis with bi-quadratic elements to investigate the results in terms of isotherms, streamlines, heatlines and average Nusselt numbers for a wide range of parameters ($1 \leq Re \leq 100$, $0.015 \leq Pr \leq 10$, $103 \leq Gr \leq 105$).

Alam et al. [44] studied the rectangular enclosures to investigate the flow inside cavity which was induced due to the constant partial heating at lower half of the left vertical wall and partial cooling at the upper half of the right vertical wall, while the rest walls were adiabatic. From their findings, observed local heat transfer increases as the aspect ratio increases. The average heat transfer rate (Nu) increases as the aspect ratio, A, increases from 0.5 to 1 and beyond that it decreases smoothly. The heat transfer rate attains its maximum value at aspect ratio one.

Aspect ratio was concluded as impacting the heat transfer rate inside enclosure. The bigger aspect ratio, the trend of heat transfer demonstrates an increment and thus gives a good design approach to be considered. However, the aspect ratio reported does not provide a specific formulation on certain different wall material when used together as inner wall.

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1.5 Effects of Baffles Arrangement

The use of baffles inside heated enclosures provides a streamline guidance and heat pathway to control stratification in heat distributions. Saravanan et al. [45] studied numerically on natural convection in an air filled differentially heated square cavity containing two vertical thin heat generating baffles. The effects of various thermal boundary conditions on the vertical walls and different position of the baffles on heat transfer and fluid flow are investigated with the Grashof number and Prandtl number are fixed at 107 and 0.71, respectively. They focused on a steady state results for the vorticity–stream function formulation and presented in the form of streamline and isotherm plots and average Nusselt numbers.

Kalidasan et al. [46], mentioned in his study that the introduction of cold baffle intensifies the heat transfer inside the enclosure irrespective of its position and length. They highlighted that the hydrodynamic blockage effect is dominant when the transverse baffle is positioned on the right side of the partition. Finite difference based numerical is used and the fluids are under steady, laminar natural convection inside the open square enclosure with protrusions. The fluid considered is air with a Prandtl number of 0.71. Temperature difference creates the buoyancy which enabled cold air flows from bottom-left vertical wall to the diagonally opposite top-right vertical wall crossing the obstacles in the form of a partition and transverse baffles.

Hussain et al. [47] conducted a study to investigate the effect of presence of insulated inclined centred baffle and corrugation frequency on the steady natural convection in a sinusoidal corrugated enclosure. Two vertical sinusoidal walls are maintained at constant low temperature whereas a constant heat flux source whose length is 80% of the width of the enclosure is discretely embedded in the bottom wall. They found that the average Nusselt number increases with the increase in both the Grashof number and corrugation frequency for different baffle inclination angles and the presence of inclined baffle and increasing the corrugation frequency have significant effects on the average Nusselt numbers, streamlines and isotherms inside the enclosure.

Promvonge et al. [48] investigated numerically on periodic laminar flow and heat transfer behaviours in a three-dimensional isothermal wall square-channel fitted with 30°-angled baffles on two opposite channel walls. Based on the finite volume method with the SIMPLE algorithm, the fluid flows in terms of Reynolds numbers ranging from 100 to 2000 generating a pair of stream wise counter-rotating vortex (P-vortex) flows through the tested channel, the angled baffles with the attack angle of 30° are mounted periodically and inline the arrangement on the lower and upper channel walls. They examined the effect when different baffle heights are applied and three pitch ratios on heat transfer and flow behaviours in the channel vary. It appears that P-vortex flows help to induce impinging flows over the baffle leading end side and the inter-baffle cavity walls resulting in the drastic increase in heat transfer rate over the test channel. The computational results revealed the maximum thermal enhancement factors for the baffle with PR = 1, 1.5 and 2 are found to be about 3.6, 3.8 and 4.0 at BR = 0.2, 0.2 and 0.15, respectively.

Oztop et al. [49] carried out a numerical simulations of the conduction-combined forced and natural convection (mixed convection) heat transfer and fluid flow performed for 2-D lid-driven square enclosure divided by a partition with a finite thickness and finite conductivity.

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Left vertical wall of enclosure has two different orientations both for positive or negative vertical coordinate. Buoyancy forces are taken into account in the system. With adiabatic horizontal walls while two vertical walls are maintained with isothermal temperature but the temperature of the left moving wall is higher than that of the right stationary wall, heat transfer regime between moving lid and partition was mixed convection.

In their study, conduction occurs along the partition and, pure natural convection is formed between the partition and the right vertical wall. The Richardson number is changed from 0.1 to 10, thermal conductivity ratio varies from 0.001 to 10. They observed that higher heat transfer was formed for higher Richardson number for upward moving wall for all values of the thermal conductivity ratio. When forced convection becomes effective, the orientation of moving lid becomes insignificant and they concluded that heat transfer is a decreasing function of increasing thermal conductivity ratio for all cases and Richardson numbers.

1.6 Effects of Heat Source Location

Heat source is the major enthalpy/energy generation inside enclosure and should be precisely placed to ensure effectiveness and continuity in heat discharge. In a recent research in the subject, Öztop et al. [50] reviewed natural convection heat transfer and fluid flow different types of enclosures with localized heating, considering the working fluid as a simple fluid or a nanofluid to investigate the effects of type and location of local heat sources as well as the effects of the different configurations of cavities and boundary conditions. Aitlahbib et al.[51] investigated square enclosure equipped with one vertical phase change material (PCM) wall, whereas the other one was kept at ambient temperature as a simplified configuration of the heat retaining system called Keeping Warm System (KWS). A transient, two-dimensional numerical model has been developed to study the coupled heat transfer in the PCM and air inside the rectangular enclosure. His findings show the effect of the PCM on the time wise variations of the gas average temperature and the Nusselt number at both cold and hot sides of the cavity. The comparison with the case without latent heat shows that the heat retention in the cavity has been significantly enhanced by the presence of a PCM wall.

Studied by Rahimi et al. [52], a rectangular enclosure model applied to representing a room and equipped with the under-floor heating system to investigate the contribution of free convection and radiation in the heat transfer from the heated floor of a room to the other internal surfaces. Their findings revealed that 75–80% of the heat is transferred by the radiation from the heated floor to the other surfaces of the enclosure. They mentioned that the contribution of the radiation decreases slightly as the floor temperature increased.

A numerical study of two-dimensional transient natural convection in a rectangular enclosure was studied by Kuznetsov et al. [53]. The cavity has finite thickness heat-conducting walls with a heat source of constant heat transfer rate located on the inner side of the left wall. Stream function, vorticity and energy equations have been solved by finite difference numerical method. The relevant governing parameters were: the Grashof number from 106 to 108, the Prandtl number, Pr=0.7 and the conductivity ratio.

Oztop et al. [54] performed numerical analyses to study the fluid flow and heat transfer due to buoyancy forces in a tube inserted square cavity filled with fluid by using control volume method. The studied cavity was heated from the left wall and cooled from the right isothermally while horizontal walls were adiabatic. A circular tube filled with air was inserted

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into the square cavity. The results were obtained for different Rayleigh numbers (Ra=104, 105 and 106), with thermal conductivity ratio of the fluid to the tube wall (k=0.1, 1 and 10) and different location centres of the tube (c (0.25≤x≤0.75, 0.25≤y≤0.75)). The result compared with benchmark solutions and it was found that varied location of the tube centre can lead to different flow fields and heat transfer intensities which are also affected by the value of Rayleigh number.

1.7 Effects of Wall Condition

The tendency for exchange of thermal energy occurs when heat dissipated from heat source or physical system to surround region inside the enclosure when temperature and pressure differences exist. Kinetics energy of particles exchanged through the boundary between two systems, which involve internal energy change that is always related with the wall surface textures and its area facing angle. Yapici et al. [55] conducted a numerical study, of steady laminar mixed-convection heat transfer in a two-dimensional square lid-driven cavity with a modified heated wall. The investigation covered a range of Richardson numbers, including 0.01, 1, and 10. The model with heated bottom wall of the cavity is characterized by rectangular, triangular, and sinusoidal wave shapes. The cooled top wall of the cavity is sliding with constant velocity, while the vertical walls are kept stationary and adiabatic. Using a finite-volume technique to solve governing equations, results presented in the form of streamlines, isotherms, and Nusselt number plots. Results demonstrated that the heat transfer enhancement is generally observed with the modification of the heated wall, while the improvement is found to be more profound for the case of rectangular wave and at low Richardson number.

Studied by He et al.[56], through basic idea called the field synergy principle (FSP), the existing mechanisms for enhancing single-phase convective heat transfer and the fundamental mechanism to reduce the intersection angle between fluid velocity and temperature gradient investigated. Based on their findings, an effective way for improving convective heat transfer performance of an existing heat transfer structure is to reveal the locations with a bad synergy (i.e., large local synergy angle) and improve the performance by changing the local structure of the surface where heat exchange occurs.

Entropy generation due to natural convection in a rectangular cavity with circular corners surface numerically was studied by Salari et al. [57]. An analysis of the entropy generation in Γ-shaped enclosure with circular corners was performed by Ziapour et al.[58]. A year later , they worked on same enclosure surface model to study enhanced finite-volume method for solving the arc-roof and the one-sided roof enclosures; with assumptions made that enclosures like two-dimensional cavities with the natural convection of air inside [59]. Double-diffusive convective flow in a rectangular enclosure with moving upper surface studied by Teamah et al. [60], concerned with the mixed convection in a rectangular lid-driven cavity with combined buoyancy effects of thermal and mass diffusion.

Investigated by Pehlivan et al. [61] on transfer rate for sinusoidal corrugated surface channel, three different types of sharp corrugation peak fins and a plain surface were setup in the experiment. For constant heat flux of 616W/m2, varied Reynolds number Re 1500 to 80q00 for the corrugation angle (27, 50 and 22/60°) and channel height of 5 and 10mm, Nusselt number (Nu), convection heat transfer coefficient (h), Colburn factor (j) and enhancement ratio (E) against Reynolds number (Re) have been studied. They concluded that any increase of corrugated angle gave rise to a heat transfer rate.

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A penalty finite element analysis with bi-quadratic elements is carried out by Basak et al. [62] to investigate the effects of uniform and non-uniform heating of inclined walls on natural convection flows within a isosceles triangular enclosure. They have considered two cases of thermal boundary conditions; case I: two inclined walls are uniformly heated while the bottom wall is cold isothermal, while in case II: two inclined walls are non-uniformly heated while the bottom wall is cold isothermal. For various Rayleigh numbers (Ra), (103⩽Ra⩽106) and Prandtl numbers (Pr), (0.026⩽Pr⩽1000, they found that at small Prandtl numbers, geometry does not have much influence on flow structure while at Pr=1000.The stream function contours are nearly triangular and showed that geometry has considerable effect on the flow pattern. The presence of multiple circulations observed for small Pr (Pr=0.026) which causes wavy distribution of local Nusselt number. Finally they stated that non-uniform heating produces greater heat transfer rates at the centre of than the walls than the uniform heating; meanwhile average Nusselt numbers show overall lower heat transfer rates for the non-uniform heating case.

From detail reviews on wall effect in heated enclosure studied by past researchers, it could be summarized that wall surface structure, inclination angle and diffusivity give significant impact for heatline, massline and velocity profile with various dimensionless thermal parameters effect.

2.0 CONCLUSION

This paper presents an inclusive review on the geometrical and thermal parameters for integrated heated enclosures design. Although many geometrical aspects were studied, it is still a challenge to design hybrid shaped enclosures for certain specific purposes, and without degrading the thermal performance of both coupled geometrical shape. The use of relevant software to solve the governing equations and for predicting the thermal behaviours is economical rather than experimental methods alone.

Adaptation approach is a better solution to integrate all parameters for designing new generation thermal heated enclosures. Lack of studies concerned with hybrid shape oriented design efforts for catering the problems which specified with new practical used. Combining rectangular and triangular shape for example, will help to improve airflow circulation in machineries, buildings, vehicles, and food processing and electronics application. Adaptation design is not just limited to the geometrical shape, but could be extended to the configuration inside heated enclosure. Redefining the baffles and wall arrangement with effective inclination angle, will help to enhance thermal distribution and heat uniformity recovery in time-temperature based operation. Selecting the optimal aspect ratio not only improves the thermal efficiency, but also helps the designer to make estimation for material and sizing considerations to avoid over size or undersize enclosures for specific task.

Corresponding to the current energy conservation demand due to the rising awareness on global warming and greenhouse effect, it is time to redefine the heated enclosure design which capable to cater both demands to reduce energy intensity and efficiency, energy conservation and minimizing environmental impacts. Waste heat recovery approach as the replacement heat source inside the heated enclosures is just one piece of great strategies to put on eye. By solving these challenges, it is expected that an integrated adaptation approach

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can make substantial impact in heated enclosure design, in line with the effort to contribute better environmental and economic impact.

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