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CHAPTER - I

INTRODUCTION

1.1 INTRODUCTION :

Study of free convection in rectangular enclosures is the subject of interest since long, particularly because of its application in variety of fields. Design optimization of equipments such as room heaters, window glazings, solar collectors, cryogenic storages, thermal insulations, air-filled cavities of thermally insulated walls, gas-filled cavities in nuclear reactors, furnaces etc. is primarily centered on estimation of free convection losses in such equipments. Somewhat recent application of manufacturing in outer space where materials like semi conductors, metals, glasses and medico-biological crystals are grown under micro-gravity, requires up-to-date knowledge of free convection in cavities of various shapes and sizes. This is because presence of convection gives rise to macro and micro-inhomogeneities in crystals which should be closely controlled for producing pure materials.

Free convection in rectangular enclosures can be broadly divided into three categories :

i) Boundary layer convection in vertical enclosures
- Heated from sides case.

ii) Cellular convection in inclined enclosures under favourable temperature gradients :
- Heated from above case, bottom heavy arrangement.

iii) Cellular convection in inclined enclosures under adverse temperature gradients :
- Heated from below case, top heavy arrangement.

1.1.1 Boundary layer convection in vertical enclosures: Here, hot and cold surfaces face each other vertically while remaining two surfaces are either insulated ($\partial T/\partial x$ = 0), heat conducting ($\partial T/\partial x$ = constant) or isothermal (T= constant). Convection in this case is of localised nature and is within the boundary layers formed along both hot and cold vertical surfaces, while the central core is free from convection and heat transfer takes place, in this region, purely by conduction. The size of the this central core depends upon the width of the enclosure. This central conducting core may disappear completely if the boundary layer thicknesses approach or exceed the width of the enclosure, in which case, the boundary layers are said to interact with each other. This case has been abundantly studied and well understood, both analytically and experimentally.

1.1.2 Cellular convection in inclined enclosures under favourable temperature gradients : Here, hot and cold surfaces face each other at an inclination such that cold surface remains below hot surface. This results in decrease in temperature and increase in density of the fluid trapped between the surfaces, along the direction of gravity vector. This is the **heated from above case or bottom heavy arrangement** and is due to negative temperature gradient i.e. positive density gradient, along the direction of gravity. This is most favourable for pure conduction from hot surface to cold surface and is responsible for supressing convection. Thus, on the whole, convection in this case will be conduction dominated and in particular, for horizontal orientation, it has been observed that convection is totally supressed by conduction. Though this case has been studied in literature, whether the gap height and width (i.e. aspect ratio) has any influence on the results, has not been fully ascertained.

1.1.3 **Cellular convection in inclined enclosures under adverse temperature gradients :** Here, hot and cold surfaces face each other at an inclination such that cold surface remains above hot surface. This results in increase in temperature and decrease in density of the fluid trapped between the surfaces, along the direction of gravity vector. This is the **heated from below case** or **top heavy arrangement** and is due to positive temperature gradient i.e. negative density gradient, along the direction of gravity. This temperature gradient is said to be adverse since, on account of thermal expansion, the fluid at the bottom will be lighter due to higher temperature, than the fluid at the top, resulting in a top heavy arrangement which is potentially unstable.

Because of this instability, the fluid will try to redistribute itself and remedy the weakness in its arrangement. However, this tendency of the fluid will be counteracted by itself due to its own viscosity. Thus, it is expected that the adverse temperature gradient must exceed a certain value before the instability can manifest itself. What actually happens at the onset of instability is that the layer of fluid resolves itself into number of cells, which eventually become equal and they align themselves to form a regular hexagonal pattern. This cellular character of fluid motion between hot and cold surfaces is most predominant for horizontal orientation, while at an inclination, boundary layer flow near surfaces, interact with cellular flow within the central core, resulting in complex fluid flow behaviour of three dimensional nature augmenting the instability. As the cellular flow is supposed to depend upon the gap height and width (i.e. aspect ratio), fluid flow and heat transfer, in this case, necessarily should depend upon aspect ratio. This has not been fully ascertained, however, in earlier ivestigations.

1.2 LITERATURE SURVEY :

Amongst all the three modes of heat transfer, convection appears to be most fascinating because of its interaction with fluid flow. As was pointed out by Brown[1], the term "convection" was coined by William Prout[2] in 1834 for the phenomenon of propagation of heat in fluids. Count Rumford[3] in 1870, described for the first time, this phenomenon in detail. As convection is always accompanied by fluid motion, depending upon how this motion is obtained, it is sub-divided into natural or free convection and forced convection.

Free convection in horizontal layers of fluid, heated from below, is the subject of interest since long, particularly, because of its application in variety of fields. James Thomson[4] stuided thermal convection in horizontal layers of fluid, heated from below and observed, for the first time, cellular character of fluid motion in 1882. Benard[5,6] presented, for the first time in 1900, quantitative results and depicted the onset of thermal instability in fluid layers heated from below.

Benard's experiments established in a definitive manner, the fact that a certain critical adverse temperature gradient must be exceeded before instability can set in. This is due to the effect of viscosity which counteracts buoyancy forces developing due to adverse temperature gradients. On surpassing this critical temperature gradient, an instability develops in the fluid layer, resulting in fluid motion of stationary cellular character. This is because of natural tendency of fluid to accomodate any instability within itself by redistributing itself into number of cells, forming a regular hexagonal pattern.

Lord Rayleigh[7] in 1916, presented a theoretical analysis and showed that what decides the stability or otherwise of a layer of fluid heated from below, is the numerical value of a dimensionless parameter $Ra = \frac{\beta g (|d\theta/dz|) H^4}{\alpha \nu}$

where β , α and ν are volumetric coefficient of thermal expansion, thermal diffusivity and kinematic viscosity respectively, H is the layer thickness and / d0/dz/ is the absolute value of uniform adverse temperature gradient (= $\Delta T/H$) which is maintained for steady heat flow. Rayleigh also showed that for instability to set in and for convection to start, Ra should exceed a certain value Ra_c, known as **critical Rayleigh number.**

A detailed analytical and experimental study of thermal instability of a fluid layer heated from below, was made by Chandrasekhar[8] in 1957, full account of which appeared later[9] in his treatise in 1961. The book also gives complete bibliographical notes on the subject. Analytical study included the use of Boussinesq approximation[10] in the governing equations to arrive at critical Rayleigh numbers for even and odd modes, after employing variational principles due to Pellew and Southwell[11] and Chandrasekhar[12]. Analytical solutions presented by Low[13], Reid and Harris[14,15], Christopherson[16] and Bisshopp[17] have also been included in the treatise. Experimental study covered Benard's[18] experiments, Schmidt - Milverton Principle [19] and experimental findings of Schmidt and Saunders [20], Saunders et al[21], Malkus[22] and Silveston [23]. It was observed that experimental value of Ra_c for the onset of cellular convection agrees reasonably well with that obtained analytically. Schlieren observations indicated emergence of the cell pattern at critical Rayleigh number and its stability far beyond marginal conditions.

In 1932, Schmidt[24] observed fluttering motion of air above heated plate, using Schilieren apparatus. Jakob and Linke[25] obtained one-third power law for Nu-Gr relationship, while Kraus [26] observed in 1940, random vortices above the plate. Chang [27] in 1957, postulated hydrodynamic wave theory for explaining free convection above heated horizontal plates, which can conveniently explain the cellular structure of convective instability. Mikheyev[28] on the other hand, imagined distributed regular vortices rotating in opposite sense consequtively. Tarasuk et al[29] suspected three distinct flow patterns in an optical investigation and advocated further study. Wragg and Loomba [30] studied free convection mass transfer from horizontal circular plates using an electrochemical technique, while Goldstein et al[31] in 1973, obtained a single correlation for free convection mass transfer from horizontal plates of circular, square and rectangular profiles, using sublimating napthalene models. The author[32] studied the problem using mass transfer analogy [33], employing Powell and Griffith's technique[34] and obtained a correlation confirming with Mikheyev's results[28].

Free convection above rectangular plates is modified due to surface tension effects on the free surface while free convection in rectangular enclosures is free from such free surface effects due to their rigid boundaries. Ostrach[35] in 1972, reviewed contemporary investigations in the field of free convection in vertically oriented rectangular cavities. Of particular mention is Eckert and Carlson's[36] and Elder's[37,38] work which he discussed fully and Newell and Schmidt's[39] paper in which effect of aspect ratio was investigated analytically.

Hollands et al[40] in 1975, performed experiments on free convection in horizontal air and water layers, however, they did not alter enclosure spacing and hence aspect ratio was maintained constant in their experiemnts. Charan et al[41] reported results on inclined enclosures under adverse temperature gradients and gave a correlation including the effect of orientation. They covered only two aspect ratios in their experiments and did not attempt to find effect of aspect ratio. Shembharkar et al[42] employed conservative upwind finite difference scheme to get finite difference equations for a vertical enclosure and obtained a solution using successive point relaxation iterative method. Venkateswarlu et al[43] also studied the same problem analytically using variational approach and the concept of local potential and proposed a correlation including the effect of Prandtl number and aspect ratio.

In 1976, Buchberg et al[44] reviewed the literature on free convection in enclosed spaces from point of view of solar collector application, where they also indicated that enclosures for solar collectors are essentially high aspect ratio type (i.e. AR ranging between 20 to 200). They investigated two region and three region correlations in addition to Hollands et al's [45] correlation and recommended the use of any of them for solar collector application. None of these correlations include the effect of aspect ratio.

Hollands et al[45] experimented on inclined air layers (0° upto 60°), by changing air pressure from 10 Pa to 700 KPa for varying Rayleigh number over a wide range (upto $Ra=10^5$), without altering air layer thickness or temperature difference. They observed that Nusselt number can not be represented as a simple function of $Ra \cdot Cos\phi$ only and proposed a correlation which fitted their data. As they maintained constant aspect ratio of 48, its effect on heat transfer could not be obtained. Oosthuizen [46] studied numerically, three-dimensional buoyancy induced convection over vertical plates and cylinders. He contended that three-dimensional flow occurs if the body is inclined with respect to gravity vector or if there exists a longitudinal accleration component on the body. The governing equations were solved, after normalising and converting into finite difference form, using Thomas algorithm. They observed that for very small and very large dimensionless Z values (layer thickness), convective flow is essentially two-dimensional. Ozoe et al[47] concurrently studied analytically, three-dimensional behaviour of free convection in a fluid confined in a horizontal rectangular enclosure, heated from below. They solved the normalised governing equations using a general three-dimensional alternating direction implicit (ADI) method due to Brian [48]. They observed that for infinte horizontal plates (i.e. infinite AR enclosures), two-dimensional flow is produced while for a cubical enclosure, two stable three-dimensional circulations were observed.

Arnold et al[49] investigated the effect of orientation on free convection across rectangular regions, of different aspect ratios, experimentally. Their results compared favourably with Catton et al's[50] theoretical predictions who used Galerkin method to get a solution. Catton et al's predictions indicated a pronounced aspect ratio dependency for $0.2 \leq AR \leq 20$, considered by them. However, they presented a simple scaling law for Nu which is only a function of angle of inclination. Arnold et al concluded in their paper that a simple scaling law can not be used for $\theta \leq 90°$ where due to adverse temperature gradients, the flow becomes complex and thus, further theoretical study in this regime was indicated. They also advocated further work for aspect ratios less than 1.

Analytical study of free convection in rectangular enclosures invariably included the use of Boussinesq approximation[10], as it resulted in simplifications of governing equations. The validity or otherwise of this approximation was investigated by Gray and Giorgini[51] in 1975 and more recently in 1985, by Gartling and Hickox[52]. Both the papers reported allowable ranges of temperature differences and layer thicknesses for the validity of Boussinesq approximation.

Abdel-Khalik et al[53] in 1978, presented a finite element solution for free convection in enclosures of non-rectangular shape (i.e. compound parabolic side walls). They gave a full account of the finite element method adopted by them, which is of general validity for solving all kinds of two-dimensional, second order, non-linear problems.

Sayigh[54] in 1979, documented Hollands'[40] and Tabor's[55] correlations, while Hollands[56] elaborately discussed free convection in solar collectors. He conteded that for $AR > 20$, effect of aspect ratio is slight and can be ignored. He also discussed[57] reduced pressure solar collectors in which air pressure was reduced to elliminate free convective fluid motion and evacuated collectors in which high vacuum was maintained which not only elliminated free convection but also reduced thermal conductivity of the fluid.

Linthorst et al[58] obtained flow pictures using smoke injection and laser doppler anemometer (LDA) measurements from inclined airfilled enclosures. They observed secondary and tertiary motion for vertical orientation, while for horizontal orientation, torus-like flow pattern was obtained for $1 \leqslant AR \leqslant 7$. At all inclinations in first quadrant, transition from stationary to non-stationary flow and from two-dimensional to three-dimensional flow occured and the critical Reyleigh number for the onset of such instability was observed to increase with decrease in AR for $1 \leqslant AR \leqslant 7$.

In 1982, Elsherbiny et al[59], while surveying exhaustively earlier experiments, obtained correlations including the effect of aspect ratio for enclosure inclinations between 60° and 90° with reference to horizontal. Although, they varied AR from 5 to 110 (six values), their study was restricted to near vertical layers only.

Strada and Heinrich[60] obtained numerical results for high Ra laminar circulation in inclined enclosures using penalty function finite element algorithm. They varied angle of inclination from 0° to 180° while three values of aspect ratio (1,5 and 10) were considered. They observed that with increase in aspect ratio, the degree of difficulty in reaching solutions also increases and use of finer mesh becomes essential. This would, of course, result in significant increase in computational expenses with increase in aspect ratio and Rayleigh number.

Schinkel and Hoogendoorn[61] observed in 1983, that free convection in enclosures is influenced by the boundary conditions of the hot wall. For an isoflux hot wall, the losses are larger than for an isothermal hot wall. This effect increases with angle of inclination.

Effect of density inversion of water on free convection from inclined rectangular enclosures, was obtained by Inaba and Fukuda[62] in 1984. They observed that density inversion causes the appearance of two counter eddies whose influence on free convection is strongly dependent upon enclosure inclination.

Symons and Peck[63] studied free convection in inclined longitudinal slots. They observed that heat transfer is independent of orientation for inclinations upto 15° from horizontal, but longitudinal slots are more effective in supressing convection than transverse slots for $24° \leq \phi \leq 75°$ at the same aspect ratio.

Prasad and Kulacki[64] investigated effect of aspect ratio on flow structure and heat transfer in a vertical rectangular enclosure numerically, using a procedure developed by Gosman et al[65] and Roche[66]. They summarised the effect of aspect ratio on heat transfer by a family of curves of Nu V/s AR with Ra as a parameter for Ra upto 10^4 and AR from 0.05 to 100. They also indicated the existence of various flow regimes and correlated them in terms of aspect ratio and Rayleigh Number.

An excellent monograph on manufacturing in outer space[67] published in 1984, discusses fully, free convection from enclosures in microgravity. This study is important from the fact that presence of adverse temperature gradients is capable of producing a variety of local convective structures which may give rise to macro and micro inhomogeneities in crystals, which are grown under microgravity, on board space vehicles, for purity.

Zhong et al[68] in 1985, studied variable property free convection in tilted square enclosures analytically using finite difference schemes and stability criteria developed earlier[69], after normalising governing differential equations, following suggestions of Ostrach[70].

They attributed discrepancies between experimental and numerical results of earlier investigations to : (i) Mismatch in thermal boundary conditions between the two methods (ii) three-dimensional effects (iii) Boussinesq approximation and (iv) constant property approximation. While noting, from the study of Ozoe et al[71], that three-dimensional effects are insignificant as long as the third dimension is over twice the height or width of the cavity, they used ideal equation of state for the gas instead of Boussinesq approximation in addition to variation of transport properties with temperature, for the gases (air and CO_2) in their numerical study.

Zhong et al observed that there are at least three mechanisms for the effects of tilt. For ϕ close to 180° (heated from above case), pure conduction dominates. As ϕ reduces from 180° towards 90°, convenction starts exerting its influence due to increased gravitational effects along hot and cold walls. Also, there is an additional flow due to unstable temperature gradients in the enclosure. For $90° \leqslant \phi \leqslant 180°$ (enclosure heated from above), all these three effects are additive, while for $0° \leqslant \phi \leqslant 90°$ (enclosure heated from below), last two convective effects oppose each other, increasing the instability of the flow and eventually converting the two-dimensional flow into three-dimensional one. They refrained from giving any correlation in this region, as their data in this region, did not show any regular pattern.

Sobhan et al[72] recently studied transient free convection in a horizontal fin array using differential interferometry. They also included in their study, preliminary investigations on inclined enclosres. Only limitation of their work is that it is suitable for only transient convection and that elaborate computations are needed to quantify their results.

The author with his guide[73] presented in 1987, intermediate results, of their numerical study on free convection in horizontally oriented rectangular enclosures. The results show a strong dependence of aspect ratio on convective heat transfer. Their another paper[74] on convective heat losses in solar cookers, ~~to be~~ presented at the annual convention of Solar Engery Society of India, ~~to be~~ held at Udaipur ~~Hyderabad~~ in December, 1989, uses their earlier results[73], to arrive at a design curve for conservative gap height in solar cookers, which is a strong function of aspect ratio.

1.3 PRESENT INVESTIGATION :

Foregoing survey of existing literature on the subject reveals that though some of the investigators suspected an effect of aspect ratio on free convection from rectangular enclosures, it was ignored by most of them. Present study, therefore, aims at conducting numerical experiments to investigate the effect of aspect ratio on free convection from rectangular enclosures.

Rectangular enclosures of aspect ratios varying from 1 to 300, oriented horizontally i.e. enclosures heated from below and heated from above, are proposed to be considered in the range of Rayleigh numbers, from 66 to 1.8×10^7, for air as an enclosed fluid, having a constant Prandtl number of 0.7. It is also proposed to study the possibility of extending the investigation further to include inclined enclosures.