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PERIODIC NATURAL CONVECTION INSIDE LARGE DIMENSIONS (HIGH RAYLEIGH NUMBER) ENCLOSURES

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Abstract

Natural convection inside large dimensions rectangular enclosures of low and moderate aspect ratios is investigated numerically. The enclosures are air filled with adiabatic horizontal walls and isothermal (with different temperatures) vertical walls. The studied range of Rayleigh number is from Ra = 10^6 to Ra = 10^{10} (based on either the enclosure height or width). The effect of the enclosure aspect ratio (between 0.25 to 6), temperature difference (betweren 5^oC to 40^oC), and enclosure dimensions (height * width varies between 0.15 m x 0.15 m up to 3.0 m * 6.0 m) on flow and thermal fields are presented. It was found that for values of Rayleigh numbers greater than 4 * 10^6, a periodic variation (Oscillations) in both flow and thermal field takes place. The flow pattern and the envelops of velocity and temperature variations (oscillations amplitudes) are presented in details. The predicted results are in agreement with recent experimental work.

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Nomenclature

A	Aspect ratio L/H	
g	Gravitational acceleration	m/
Gr_H	Grashoff number based on Width H	
Gr_L	Grashoff number based on hight L, $Gr_L = \beta g(T_h - T_c)L^3/\nu^2$	
H	Width of the enclosure	m
k	Thermal conductivity	W/m^oC
L	Height of the enclosure	m
p	Pressure	N/m^2
Pr	Prandtle number $Pr = \nu/\alpha$	
Ra_H	Rayleigh number based on width H, $Ra_H = \beta gH^3 \Delta T/\nu\alpha$	
Ra_L	Rayleigh number based on height L, $Ra_L = \beta gL^3 \Delta T/\nu\alpha$	
t	Time	s
T	Temperature	^oC
T_c	Cold wall temperature	^oC
T_h	Hot wall temperature	^oC
T_o	Reference temperature $T_o = (T_c + T_h)/2$	
u	Velocity component in x-direction	m/s
u_o	Velocity component in x-direction at x/L = . 55	
v	Velocity component in y-direction	m/s
v_o	Velocity component in y-direction at x/L = .95	m/s
x	Coordinate in x-direction	
y	Coordinate in y-direction	

Greek Letters

α	thermal diffusivity	m^2/s
β	Volumetric coefficient of expansion	1/K
Δ	incremental step size	

ν	Kinematic viscosity	m^2/s
ρ	density	kg/m^3
θ	Dimensionless Temperature Difference $\theta = T-T_o/T_h-T_c$	

1. Introduction

Two dimensional buoyancy driven flows within large dimensions rectangular enclosures, Figure (1), have received much attention during the past three decades. The reasons are the geometric simplicity that makes experimental and numerical simulation attractive; and the many practical heat transfer situations in which they arise. For example detailed information of the flow and thermal fields in buildings heating and cooling (solar houses, nuclear reactor containments, ... etc), and certain processes in environmental and geophysics (dispersion of pollutant in buildings, buoyancy driven flow in bodies of water ... etc) are governed by natural convection.

Experiments of Hurle et. al. [1], Hart [2], and Briggs and Jones [3] established that the buoyancy-driven flow which ensues as soon as $T_1 \neq T_2$ becomes oscillatory beyond a certain value of Rayleigh number. For example, Briggs and Jones [3], experimentally studied the case of aspect ratio equal one (for air, Pr= 0.7). The authors clearly define the existence of periodic laminar flow regimes at Rayleigh number above $3x10^6$. The periodic variation in velocity is reported to be induced by the upper and lower boundary conditions (linear temperature gradient). The authors reported the envelops of vertical and horizontal velocity components fluctuations and indicated two distinct flow regimes over the modest change in Rayleigh numbers, from 10^6 to $12x10^6$. At Rayleigh number below $3*10^6$, no periodic flow was detected and the flow was purely circulatory. For Rayleigh number between $3*10^6$ and $12x10^6$, very regular periodic flow was observed with one or two modes of frequency. On the other hand, very recently Winters [4] numerically showed that the steady solution of the Novier-Stokes equations in a cavity with hot/cold vertical walls bifurcates at a critical Rayleigh number to an unsteady oscillating solution. The bifurcation of Navier-Stokes solution shows interest such that an international workshop will be organized in October 1988, reference [5], to construct a "benchmark" for oscillatory convection.

The current work was prompted as an attempt to simulate such oscillatory laminar natural convection for large dimensions enclosures (high Rayleigh numbers $Ra > 10^6$). As an extension of the work carried-out by the author , Reference [6], the effect of enclosure aspect ratio, enclosure dimensions and temperature difference will also be studied.

2. Analysis

Figure (1) illustrates the two dimension enclosure in which the hot

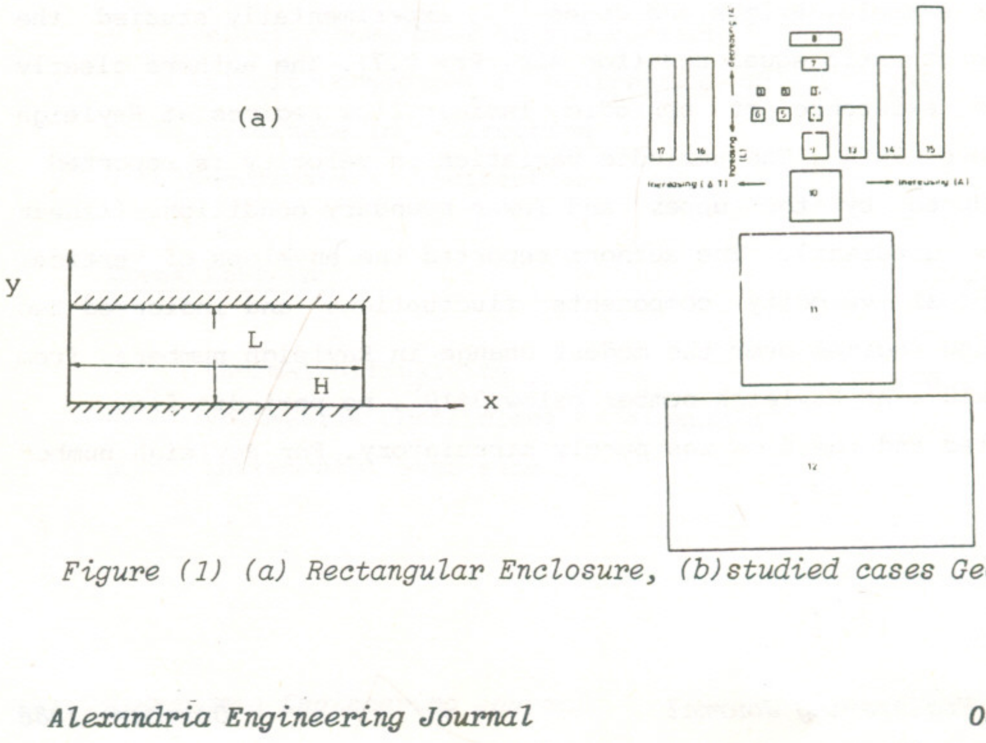


Figure (1) (a) Rectangular Enclosure, (b)studied cases Geometries and cold vertical (isothermal) walls are maintained at two different temperatures, T_h and T_c, while the two horizontal walls are adiabatic. For laminar, natural convective motion, the hydrodynamic and thermal characteristics are governed by the conservation of mass, momentum and energy equations. The governing equations and the numerical solution are very much similar to that described in reference [6].

3. Code Verification

a. Experimental

The present numerical technique was qualitatively tested against a simple experimental air cell of horizontal temperature gradient. A schematic diagram of the experimental arragmenet is shown in Fig. (2.a). Specific details associated with this test cell are described.

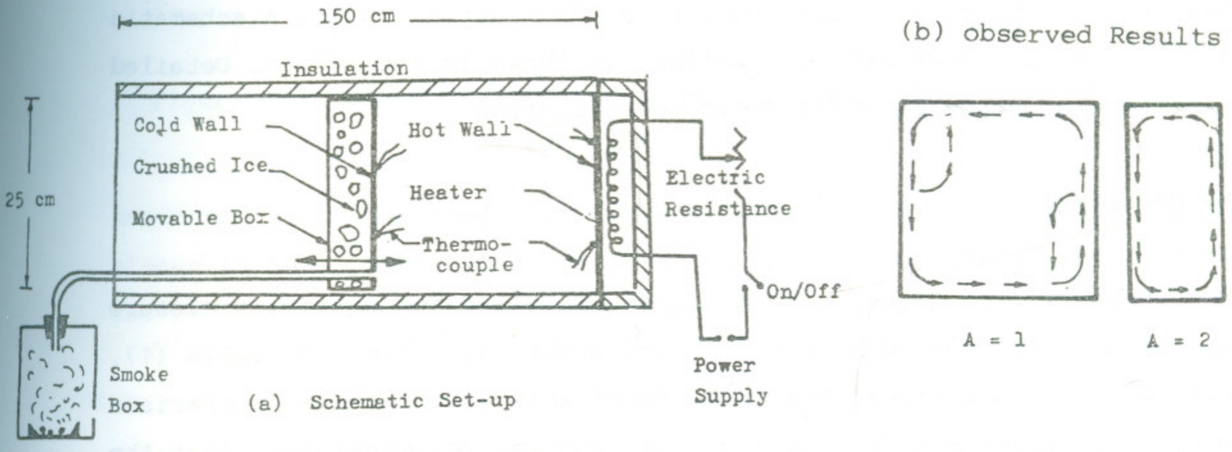


Figure (2) Experimental Set-up and Observed REsults.

The interior dimensions of the enclosure were: height 25 cm; depth 30 cm; distance between the fixed hot and movable cold plates can vary between 10 cm to 140 cm. The cold plate was connected to a flexible movable box containing a constant temperature cold fluid (usually crushed ice with distilled water at zero degree). The fixed hot plant was located in front of an electric heater of variable power supply. The two ends of the enclosure were of glass to allow the visualization of the flow fields. Top and bottom walls of the enclosure were insulated. The temperature difference between the two (vertical) isothermal walls were measured by copper-constantan thermocouples. A brief flow visualization study was conducted to obtain information on the overall flow patterns present in the enclosure. Several different methods were used including smoke and particle tracing. The flow visualization indicated that the flow field is characterized by a main vortex confined to a region adjacent to the walls. Smaller secondary recirculation areas were obtained mainly at high temperature difference (high Rayleigh number) and low aspect ratio. A schematic sketch of an observed flow pattern is shown in Fig. (2.b). Detailed experimental study is still under investigation.

b. Numerical

The present technique was used to simulate the shallow enclosure experimentally studied by Nansteel and Greif [7], Case (19) Table (1). Figure (3) summarizes the results of this simulation in comparison with the experimental results. It should be mentioned that the oscillation in flow and thermal field was not observed by Nansteel and Greif [7]. The flow field is characterized by a main vortex near the enclosure boundary (as observed by Nansteel and Greif [7]) in addition to secondary vortices in the core region. A comparison between the

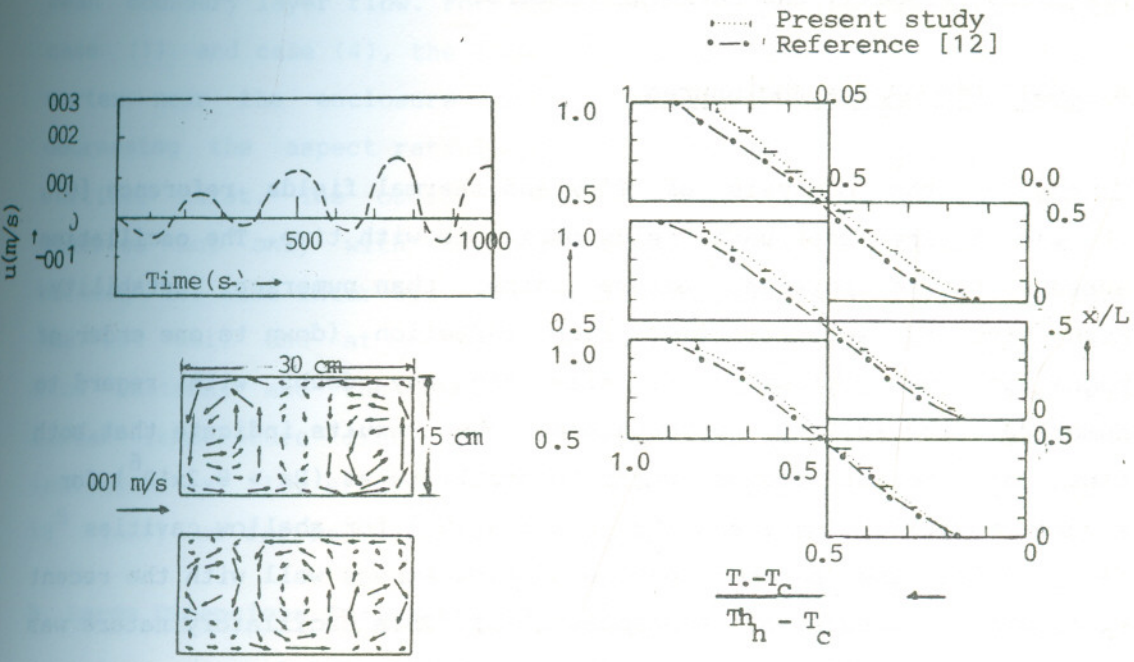


Figure (3) Numerical Simulation of Reference [12], case (19).

predicted and measured temperature profiles at different vertical planes is shown which shows good agreement. The horizontal lines along the predicted results represents the range of temperature oscillation.

4. Results and Discussion

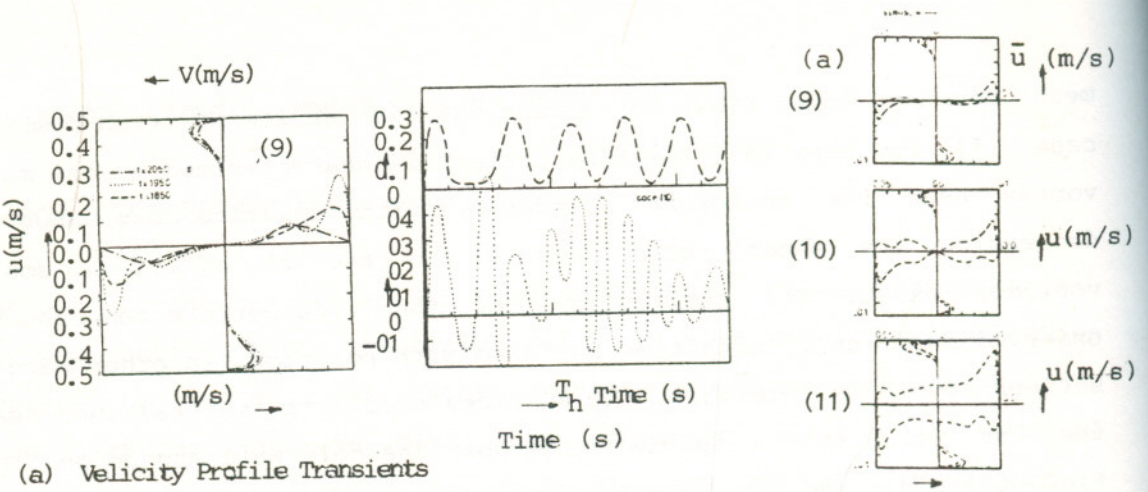
Figure (1.b) gives an illustration of the studied cases. All the data related to these cases are given in table (1). The data included the temperature difference between the two isothermal walls, (LXH) distances, Prandtl, and Rayleigh numbers.

A. Small Dimensions Enclosures

Throughout the analysis of flow and thermal fields reference [6], it was noticed that both fields oscillate with time. The oscillation appears to be physical nature rather than numerical instability. Mesh size as well as time step reduction (down to one order of magnitude) was performed to eliminate any doubt with regard to numerical instability. Neverthless, the results indicate that both flow and thermal fields start to oscillate at $(Ra > 8.2 \times 10^6)$ for square cavities $(A=1)$ and $(Ra_1 \geq 4.1 \times 10^6)$ for shallow cavities $(A \leq 0.5)$. The periodic nature of flow agrees well with the recent experimental results of references [1-3]. This oscillatory nature was not limited to the enclosure boundaries but extended to the enclosure interior. Oscillations amplitudes was found to increase with increasing Rayleigh numbers and decreasing aspect ratio. It is always higher near the walls and partially damped out as getting into the core. Briggs and Jones [3] indicated that the cause of such periodicity in their experiment was the linear temperature gradient conditions between the two isothermal walls. However, it seems that this periodicity is of general nature and a hint of getting into transitional flow. Nansteel and Greif [7] indicated from flow visualization of their experiments that fully developed turbulent flow do not exist anywhere into their enclosure, (case 19) even for Rayleigh numbers as high as 10^{11}. However travelling in wave like motion near wall (known as wall waves) were very prominent on both heated and cooled vertical surfaces. These waves, the first hint of transitional flow was found to develop at $x/L = 1/3$ and $2/3$ on hot and cold walls respectively, and travelled in the same direction as the mean boundary layer flow. For square cavities at low Rayleigh number, case (1) and case (4), the flow pattern is characterized by one main vortex near the enclosure boundaries with inactive core. However decreasing the aspect ratio, case (7) and case (8), additional small vortices exist. The oscillations of the flow pattern can also be observed not only with time but also with position. In other wards, between two time intervals, the vortices oscillate (shifts) once near the hot wall and at another time near the cold wall and so on. The flow pattern, and the temperature distribution, indicate that the linear temperature distributions along the vertical midplan (an indication of flow stratification) are no longer exist for $Ra \geq 8.2 \times 10^6$ (A=1), or for $Ra_L = 4.1 \times 10^6$ and $Ra_H > 3.3 \times 10^7$; ($A < 1$) .

B. Large Dimensions Enclosures (A = 1)

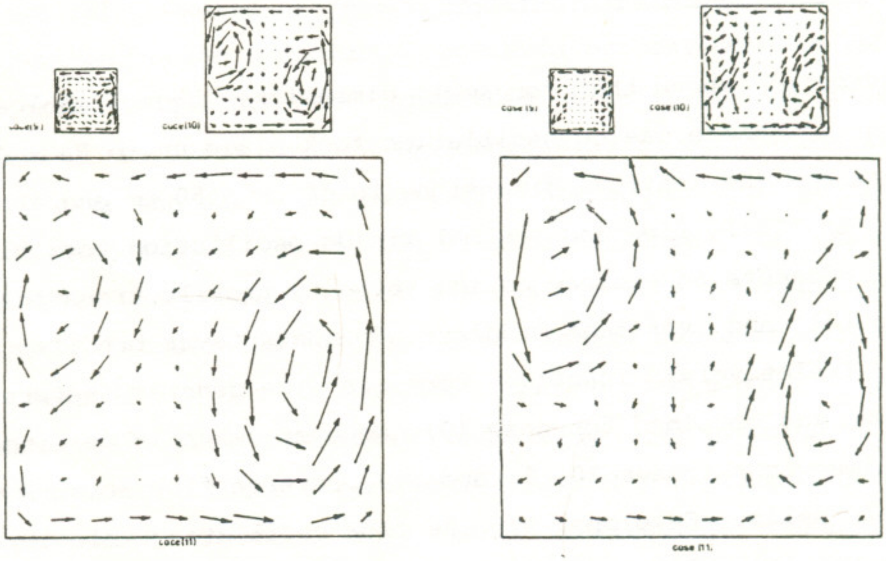
It was indicated above that for small dimensions, square enclosures (case 1 to 4), there was no oscillation took place up to $Ra = 4.1 \times 10^6$. Increasing the cavity dimensions to 50 cm x 50 cm and above (cases (9) to (12)), flow and thermal fields oscillation took place. Figure (4) presents an example of the velocity profile transients at both horizontal and vertical midplans. Boundary Layer profiles near walls with (relatively) inactive core is the general feature. No reverse flow was obtained for case (9). However, when increasing the enclosure dimensions (cases 10, 11 and 12), reverse flow appears near the vertical walls. Envelops of the flow oscillating velocity are shown in Figure (4). Flow pattern is given in Figure (5). Two strong circulating vortices are located near isothermal walls. Comparison between cases (7) and (12), A = 0.5, shows similar trend of flow pattern only when the driving velocity is maximum. Reverse flow occurs only for the large dimensions enclosures.



(a) Velicity Profile Transients

(b) Envelops of madplans velocity Oscillations.

Figure (4) Oscillation of Large Enclosures



(a) Maximum U_o

(b) Minimum

Figure (5) Flow Pettern For Square Enclosures

C. Large Dimensions Vertical Enclosures (A > 1)

Oscillation of both thermal and flow fields was also observed for large dimensions vertical enclosures A>1, cases (13) to (15). Oscillation amplitude decreases (relatively) as aspect ratio increases and as the temperature difference decreases. Oscillation of velocity component at different aspect ratios as well as the flow pattern are shown in figure (6). Similar results are obtained for different temperature differences.

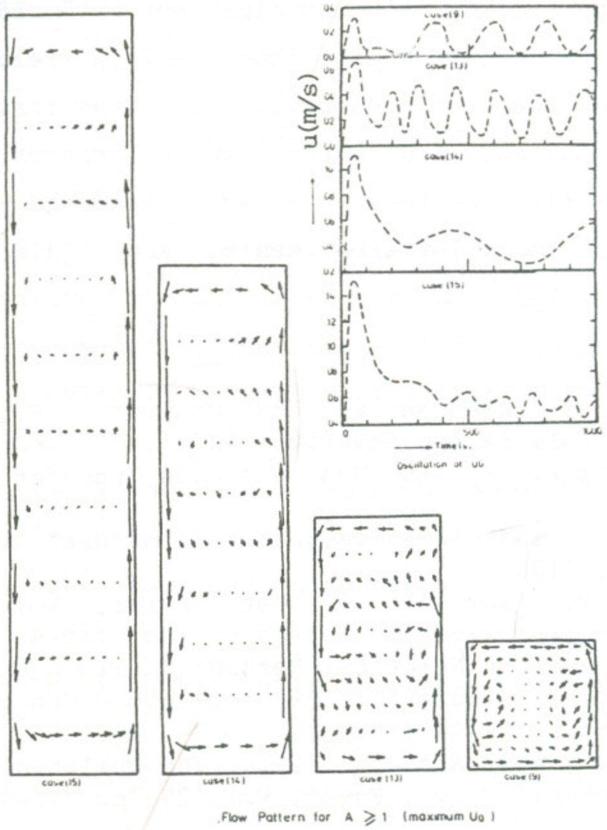


Fig. (6) Flow Pattern and Oscillation For A > 1.

5. Conclusions

A numerical investigation has been carried-out to study the flow and thermal fields of high Rayleigh number natural convection inside large dimensions rectangular enclosures. Different values of enclosures aspect ratio, dimensions, and temperature difference (Rayleigh numbers) have been considered. The results indicated the existance of periodic variations in both flow and thermal fields when Rayleigh number is above $4*10^6$. The oscillations amplitude increases with decreasing aspect ratio, increasing enclosure dimensions, and increasing temperature difference. The oscillatory flow was not limited to the enclosure boundaries but extended to the enclosure core. The flows pattern show also that the flow field is characterized by a main vortex near the boundary. This vortex travel in a wave like motion on both hot and cold vertical walls for high Rayleigh numbers. Oscillation of flow pattern was also observed with position i.e secondary vortices oscillates between hot and cold walls.

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