Transient Three-Dimensional Natural Convection in Confined Porous Media with Time-Periodic Boundary Conditions

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Abstract: *Transient three-dimensional natural convection in confined fluid-saturated porous media had been investigated numerically through this work. The geometry selected is a box with time-periodic temperature variation at the vertical sides and constant wall temperature at the top and bottom. In this investigation, the momentum equation of flow through fluid-saturated porous media had been transformed to a vector potential form and solved numerically using the Successive Over Relaxation method while the energy equation is solved using the three-dimensional Alternating Direction Implicit method. The values of the Rayleigh number under investigation are (150, 200, 250 and 300). The results are presented in a form of contour maps for the temperature and a velocity vector maps for the velocity. The results reveal that the temperature within the box is increased as the time or Rayleigh*

number increase.The Nusselt number varies inversely with the time and directly with the Rayleigh number. Two cell convective patterns are obtained in the y-z plane.

1. Introduction

Natural convection in fluid-saturated porous media is a topic that receives considerable attention in the heat transfer literature because of its many engineering applications. Several studies have focused on the dynamical behavior of such systems. Most of these works are based on Darcy's model for the flow and an averaged single equation model for the energy equation with the Boussinesq approximation for the density variation. Geometries investigated are typically rectangles, boxes, horizontal and vertical cylinders and triangles. On the other hand, the approach that is used in investigations may be analytical, numerical, experimental or any combination of these. Boundary conditions used are constant wall temperature, constant heat flux, insulated wall, finite heat transfer and any combination of these.

Holst and Aziz [1] investigated the transient three-dimensional natural convection in a cube of fluid saturated porous medium. The finite difference solution of the equations describing transient natural convection in porous media has shown that the motion may be two-dimensional or three-dimensional. The mode of the convection is dependent on the physical configuration and (Ra). The equations had been made more amenable to a numerical solution by introducing a vector potential, which may be regarded as the three-dimensional counterpart of the stream function. Numerical results indicated that under certain conditions three-dimensional motion would result in significantly higher heat transfer rates across the porous medium than two-dimensional motion at the same (Ra).

Zebib and Kassoy [2] studied and analyzed the three-dimensional natural convection in a rectangular parallelepiped of saturated porous media heated from below when the horizontal dimensions are integral multiples of the vertical dimension. Weakly

nonlinear analysis is used based on perturbation methods to calculate the possible two- and three- dimensional convection patterns. Arising from the nonlinear interaction of a pair of two-dimensional rolls which are excited at the same value of the critical Rayleigh number (Ra_c), they derived a two-term expansion for the velocity and temperature fields and for the Nusselt number (Nu).

Straus and Schubert [3] analyzed the modes of finite-amplitude three-dimensional convection in rectangular boxes of fluid-saturated porous material heated from below and with height d and horizontal dimensions l and b. They found for boxes with square horizontal cross-section l=b that the critical Rayleigh number (Re_c) for some of the simpler modes are functions of height-to-width ratio. Therefore for a given box size and values of (Ra) which are not too small, there are many two-dimensional and fully three-dimensional non-symmetric modes which can contribute to a general convective motion and the symmetric steady states.

Storesletten and Pop [4] presented analytical solutions of the two-dimensional free convection flow in a porous medium bounded by two vertical walls at non-uniform temperature. It is found that for λ=1 (symmetrical flow about the central plane, where λ is a dimensionless parameter measures the asymmetry of the imposed temperature on the bounding walls) in addition to a stagnant symmetric solution, there are non-stagnant steady symmetric and also steady antisymmetric solutions for a range of (Ra). They have shown that the stagnant flow is stable for all Ra<Π2 and unstable for Ra>Π2. When Ra=Π2 the antisymmetric and symmetric modes represent the steady non-stagnant flows which are described by exact analytical solutions of the governing equations.

Ismail [5] studied numerically the steady two-dimensional natural convection heat transfer in an inclined rectangular porous cavity with two parallel walls heated to uniform but different temperatures and with other two parallel walls adiabatic. It is found that as the aspect ratio (A) increases beyond 1 the value of (Rac) increases. Also it has been found that as the angle of inclination (θ) increases the value of (Rac) decreases. The maximum heat transfer occurs when the enclosure inclined between (35°-65°). Also they deduced that the peak in Nusselt number occurs between

$1 \leq A \leq 2.5$, depending upon Rayleigh number and inclination angle. As the (Ra) increases, the value of aspect ratio at which maximum Nusselt number takes place shift towards higher values of (A) for all values of (θ).

Transient natural convection in a square cavity filled with a porous medium is studied numerically by Selamat[6]. The cavity is assumed heated from one vertical wall and cooled at the top, while the other walls are kept adiabatic. The governing equations are solved numerically by a finite deference method. The effects of Rayleigh number on the initial transient state up to the steady state are investigated.

Ivana[7] presents A numerical study of transient three-dimensional heat conduction problem with a moving source . For numerical solution Douglas-Gunn alternating direction implicit method is applied and for the moving heat source flux distribution Gaussian function is used. An influence on numerical solution of input parameters figuring in flux boundary conditions is examined. This include parameters appearing in Gaussian function and heat transfer coefficient from free convection boundaries. Sensitivity of cooling time from 800 to 500 °C with respect to input parameters is also tested.

Unsteady flow of a viscous incompressible fluid past an infinite vertical porous plate embedded with porous medium of time dependent permeability under uniform suction velocity normal to the plate is analytically investigated by A. Sahin[8]. It is consider that, the permeability of the porous medium fluctuates with time and the free stream velocity is uniform. The transient, nonlinear and coupled governing equations are solved by series expansion method. The effects of various parameters entering into the problem on the transient velocity, transverse velocity components, temperature profile, the skin-friction and the rate of heat transfer are analyzed. It is observed that, the transient and transverse velocity as well as temperature leads to decrease with the increasing permeability parameter.

This work investigates transient three-dimensional natural convection in confined porous media driven by a warm wall with a periodically changing surface temperature. The bottom hot wall and

the top cold wall is maintained at a fixed temperature, and the other vertical sides temperature varies sinusoidally about a mean value , as shown in figure (2). The cyclic variation of the hot driving wall approximates the boundary condition found in many solar and energy storage applications, building heat transfer, and many environmental processes. Also it is common to many industrial set-ups as a result of the operation of the control system. Lastly, time variation in surface temperature occurs in electronic devices as a consequence of periodically switching the current on and off in the various electrical components.

2. Mathematical Methodology

A schematic representation of the system under investigation is shown in figure (1). The three-dimensional rectangular space containing a porous material of permeability K and fixed porosity which is saturated with a Boussinesq fluid of viscosity μ and coefficient of thermal expansion α. As shown in figure (1) the Cartesian system of coordinate's x-y-z is aligned with the horizontal dimensions Lx, Ly and vertical dimension Lz of the enclosure. The conservation equations of mass, momentum, and energy for a non isothermal flow in a porous medium are

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

$$u' = \frac{-K}{\mu_f}\left[\frac{\partial p'}{\partial x'}+\rho_f g\sin(\theta)\right] \tag{2}$$

$$v' = \frac{-K}{\mu_f}\frac{\partial p'}{\partial y'} \tag{3}$$

$$w' = \frac{-K}{\mu_f}\left[\frac{\partial p'}{\partial z'}+\rho_f g\cos(\theta)\right] \tag{4}$$

$$(\rho\,cp)_m\frac{\partial T'}{\partial t'}+(\rho\,cp)_f\left(u'\frac{\partial T'}{\partial x'}+v'\frac{\partial T'}{\partial y'}+w'\frac{\partial T'}{\partial z'}\right)=$$

$$k_m\left(\frac{\partial^2 T'}{\partial x'^2}+\frac{\partial^2 T'}{\partial y'^2}+\frac{\partial^2 T'}{\partial z'^2}\right) \tag{5}$$

It is a common practice in enclosure natural-convection analysis to first non-dimensionalize the governing equations and the boundary and initial conditions before a solution is attempted. In the non-dimensionalization process, a series of normalizing factors or scales must be introduced. Using the following variables as reference dimensions:

$$\text{Lx}:\text{length} \quad \alpha_m/Lx:\text{velocity} \quad \Delta T_o:\text{temperatue},\text{amplitude} \quad (\rho\,cp)_m\,\text{Lx}^2/\text{k}_m:\text{time}$$

$$\alpha_m\,\mu_f/\text{K}:\text{pressure} \quad \frac{Lx^2}{\left(\dfrac{k_m}{(\rho\,cp)_m}\right)}:\text{period}$$

The following new dimensionless variables are defined to be:

$$x=\frac{x'}{Lx} \quad y=\frac{y'}{Lx} \quad z=\frac{z'}{Lx} \quad u=\frac{u'}{\alpha_m/Lx} \quad v=\frac{v'}{\alpha_m/Lx}$$

$$w=\frac{w'}{\alpha_m/Lx} \quad T=\frac{T'-T_O}{\Delta T_O} \quad t=\frac{t'}{(\rho\,\text{cp})_m\,\text{Lx}^2/\text{k}_m} \quad p=\frac{p'}{\alpha_m\,\mu_f/K} \quad a=\frac{A'}{\Delta T_O}$$

$$\tau=\frac{\tau'}{Lx^2\Big/\left(\dfrac{k_m}{(\rho\,cp)_m}\right)}$$

The corresponding form of the governing equations is

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

$$u=-\frac{\partial p}{\partial x}-\frac{K\,\text{Lx}\,g\sin(\theta)}{v_f\alpha_m}+Ra\,T\sin(\theta) \tag{7}$$

$$v=-\frac{\partial p}{\partial y} \tag{8}$$

$$w=-\frac{\partial p}{\partial z}-\frac{K\,\text{Lx}\,g\cos(\theta)}{v_f\alpha_m}+Ra\,T\cos(\theta) \tag{9}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2} \tag{10}$$

Where Ra is a modified Rayleigh number for a porous medium saturated with a fluid

$$Ra = \frac{g\ \beta\ K\ \Delta T_o\ Lx}{\nu_f\ \alpha_m} \qquad (11)$$

In vector form, equations (6 - 10) will be:

$$\nabla \cdot \upsilon = 0 \qquad (12)$$

$$\upsilon = -\nabla p - G + R \qquad (13)$$

$$\frac{\partial T}{\partial t} + \upsilon \cdot \nabla T = \nabla^2 T \qquad (14)$$

Where:

$$\left.\begin{array}{l} G = [C1\sin(\theta), 0, C1\cos(\theta)] \\ R = [Ra\ T\sin(\theta), 0, Ra\ T\cos(\theta)] \\ C1 = \dfrac{K\ Lx\ g}{\nu_f\ \alpha_m} \end{array}\right\} \qquad (15)$$

Horne [9] shows that by introducing a vector potential (ϕ) of the form

$$\upsilon = \nabla \times \phi \qquad (16)$$

into the formulation, the resulting equations may be solved numerically faster and more accurately than with the formulation using the primary variables in equation (13). This vector potential satisfies identically the continuity equation. Hirasaki and Hellums [10] show that the potential is also solenoidal since the velocity is solenoidal (incompressible flow)

$$\nabla \cdot \upsilon = \nabla \cdot \nabla \times \phi = 0 \qquad (17)$$

therefore

$$\nabla \cdot \phi = 0 \qquad (18)$$

Taking the curl of equation (13) in the form:

$$\nabla \times \upsilon = \nabla \times (-\nabla p) - \nabla \times G + \nabla \times R \qquad (19)$$

And introducing equations (16) and (18) yields the following set of equations:

$$\nabla^2 \phi_x = -Ra \frac{\partial T}{\partial y} \cos(\theta) \tag{20}$$

$$\nabla^2 \phi_y = Ra \frac{\partial T}{\partial x} \cos(\theta) - Ra \frac{\partial T}{\partial z} \sin(\theta) \tag{21}$$

$$\nabla^2 \phi_z = Ra \frac{\partial T}{\partial y} \sin(\theta) \tag{22}$$

Boundary Conditions

For the momentum field, Hirasaki [10] has verified that the proper boundary condition on the normal component of velocity on all solid boundaries is satisfied if the normal derivative of the normal component of the vector potential vanishes, and if the components of the vector potential tangential to the surface vanish. These conditions for the vector potential are given below

$$\phi_x = \phi_y = \frac{\partial \phi_z}{\partial z} = 0 \qquad\qquad \text{at } z = 0, \frac{Lz}{Lx} \tag{23}$$

$$\phi_x = \frac{\partial \phi_y}{\partial y} = \phi_z = 0 \qquad\qquad \text{at } y = 0, \frac{Ly}{Lx} \tag{24}$$

$$\frac{\partial \phi_x}{\partial x} = \phi_y = \phi_z = 0 \qquad\qquad \text{at } x = 0, 1 \tag{25}$$

For the temperature field, the non-dimensional thermal boundary conditions are

$$T = 0 \qquad\qquad \text{at } z = \frac{Lz}{Lx} \tag{26}$$

$$T = 1 \qquad\qquad \text{at } z = 0 \tag{27}$$

The temperature of the vertical sides varies sinusoidally with time about a mean value, $\overline{Th}'$, with amplitude A' and period τ'. The hot wall temperature is greater than the cold wall temperature at all times, as graphically depicted in figure (2). In non-dimensional form, this boundary condition read

$$T = 1 + a\sin(2\pi t/\tau) \qquad\qquad \text{at } x = 0,1 \qquad\qquad (28)$$

$$T = 1 + a\sin(2\pi t/\tau) \qquad\qquad \text{at } y = 0, \frac{Ly}{Lx} \qquad\qquad (29)$$

Figure (1) illustrates these boundary conditions.

Initial Conditions

The flow is initiated by changing the top boundary temperature to T_o at time t = 0 and maintaining the lower boundary temperature at Th'. Therefore

$$\left.\begin{array}{ll}
T = 1 & \text{at } z = 0 \\[1.5em]
T = 0 & \text{at } z = \dfrac{Lz}{Lx} \\[1.5em]
u = v = w = \phi_x = \phi_y = \phi_z = 0 & \text{everywhere}
\end{array}\right\} \qquad (30)$$

The solution to the system of equations (10, 20, 21, and 22) with the boundary and initial conditions indicated previously will be obtained using a standard finite difference numerical method. The alternating-direction implicit (ADI) method was applied to the energy equation (10) and the equations of motion (20, 21 and 22) was arranged in the form of an elliptic equation and solved by the method of Successive Over-Relaxation (SOR). The initial temperature disturbance is followed by the solution of the vector potential equations. Then, the velocity is calculated from the vector potential and the results are used to advance the temperature to a new step. The process is repeated until the steady-state was reached. The energy balance between conduction and convection heat transfer on the bottom wall gives an equation for the Nusselt number in the form

$$\text{Nu} = -B1\int_0^C\int_0^1 \left.\frac{\partial T}{\partial z}\right|_{z=0} dx\,dy \qquad\qquad (31)$$

Where: $B1 = \dfrac{Lz}{Ly}, C = \dfrac{Ly}{Lx}$

Equation (31) is integrated numerically for each instant of time until steady state is reached within prescribed error. A computer program named by 'heat' is constructed which is written in FORTRAN language. At each instant of time, the current program calculates the velocity components (u,v,w) and the values of the temperature, Nusselt number and the vector potential (ϕx, ϕy and ϕz) in every grid point in the domain until the steady state is reached. The values of the Nusselt number in the steady convection regime with constant wall temperature boundary conditions in a box with aspect ratio of 1 have been compared with those predicted by Stamps [11] and Schubert [12] for a value of Rayleigh number of 100 and with Holst [1] for a Rayleigh number value of 60. The results of the comparison are shown in table (1) which indicates a good agreement with maximum relative deviation of 0.6%.

Table (1): Comparison with Previous Work

Ra	Nu			
	Constant wall temperature b.c.			
	Stamps[11]	Holst[1]	Schubert[12]	Present work
60	-	1.67	-	1.66
80	-	-	-	2.30
100	2.66	-	2.651	2.67

3. Results and Discussion

Transient three-dimensional natural convection had been investigated. The results of the numerical analysis are obtained with the help of a computer program. The geometry selected is a box with constant horizontals walls temperature (upper wall cold and bottom wall hot) and vary temperature with time at vertical sides as shown in   Figure (1). The discrepancy between the value of the Nusselt number decreases gradually as the grid becomes finer and therefore the case of 15×15×41 grid will be used.

The number of the grid is selected as a compromise between accuracy and speed of computation. The transient temperature distributions in a form of contour maps are illustrated in figures

(3&4) . These contour maps show the dimensionless temperature distribution in three dimensional sections in the box. These sections are selected in order to give a clear picture for the heat transfer within the box .All parameters used in these graphs are in dimensionless form. The (Y-Z) planes are selected at X=0.214 while the (X-Y) planes shown at Z=0.35 .The transient temperature distribution is cleared by selecting three times intervals which are ,t=0.003,t=0.006,and t=.012. In these figures high temperature values are deduced near the bottom and vertical walls where more heat is transferred in the direction of the box center with increasing time ,the convective flow transfers the hot fluid from the bottom and distributes it in the mid and upper layers which give the ascending and descending flows in the box .In the (X-Y)planes shows clearly that the hot fluid near the walls and become cold when moved in the direction of the box.

Figures (5&6) report the sequence of velocity vector distribution which show that the flow field is dominated by two cells filling most of the cavity rotating in opposite direction .This convective flow evolves from the heat transferred to the fluid at the bottom plane. In the X-Y planes it is clearer that the velocity vectors moves up. The other set of figures shows the behaviors of the flow but with different Rayleigh number as shown in figures (7 to 18) and from comparison one can deduce that the temperature values within the model are increased rapidly with time and more curvilinear temperature distribution pattern owing to the increase in the heat transferred to the box evolves from the increase in the Ra value.

Figure (19) shows that the Nusselt number varies inversely with the time and directly with Rayleigh number.
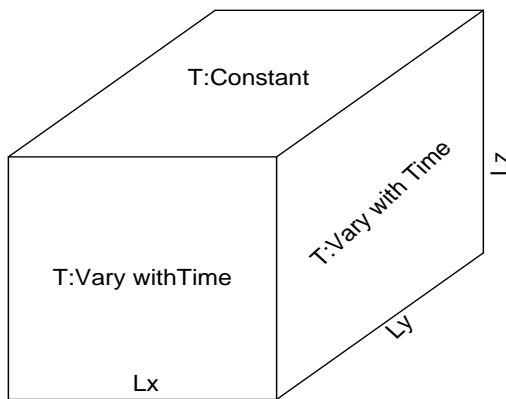
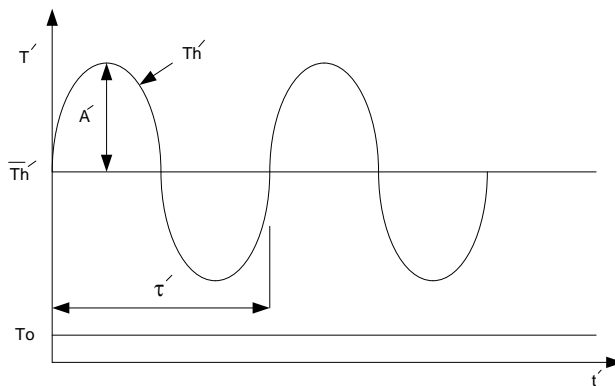**Fig. (1): The Cubic Box Boundary Conditions**

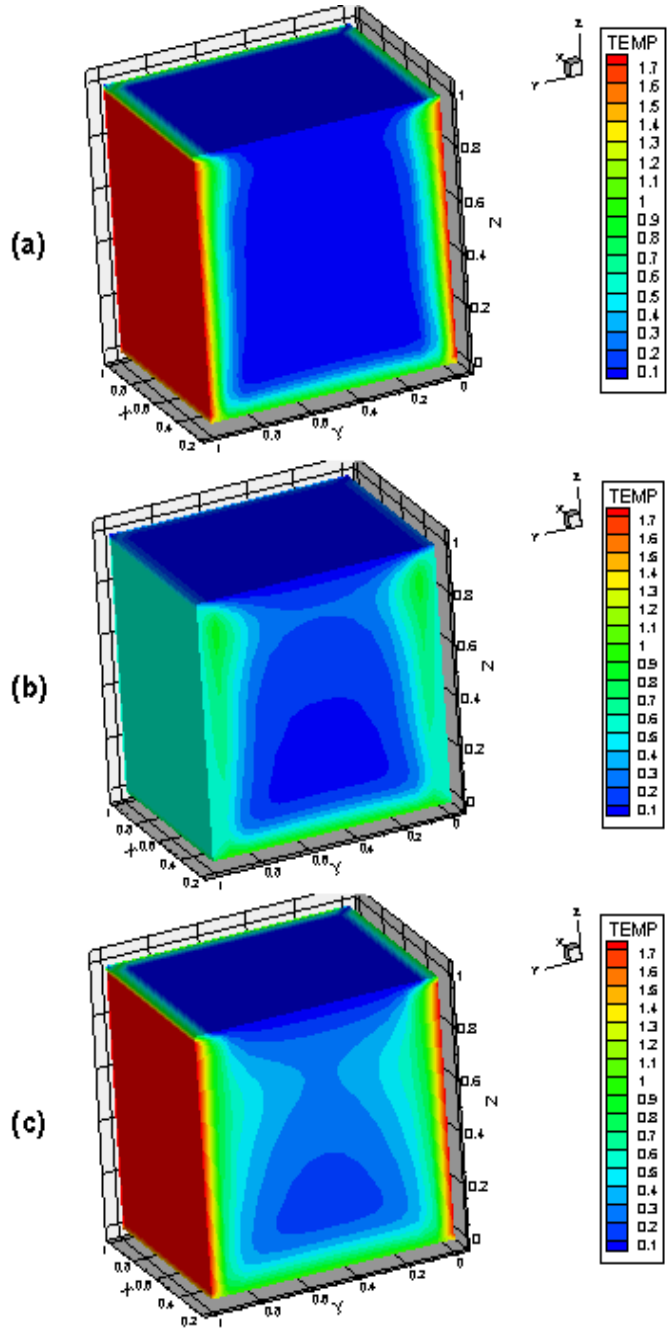**Fig.(2) : Periodically Variation of Temperature with time**

Fig. (3): Three Dimensional Transient Temperature Distribution at Section (x=0.214) for Ra=150, (a) t=0.003, (b) t=0.006, (c) t=0.012
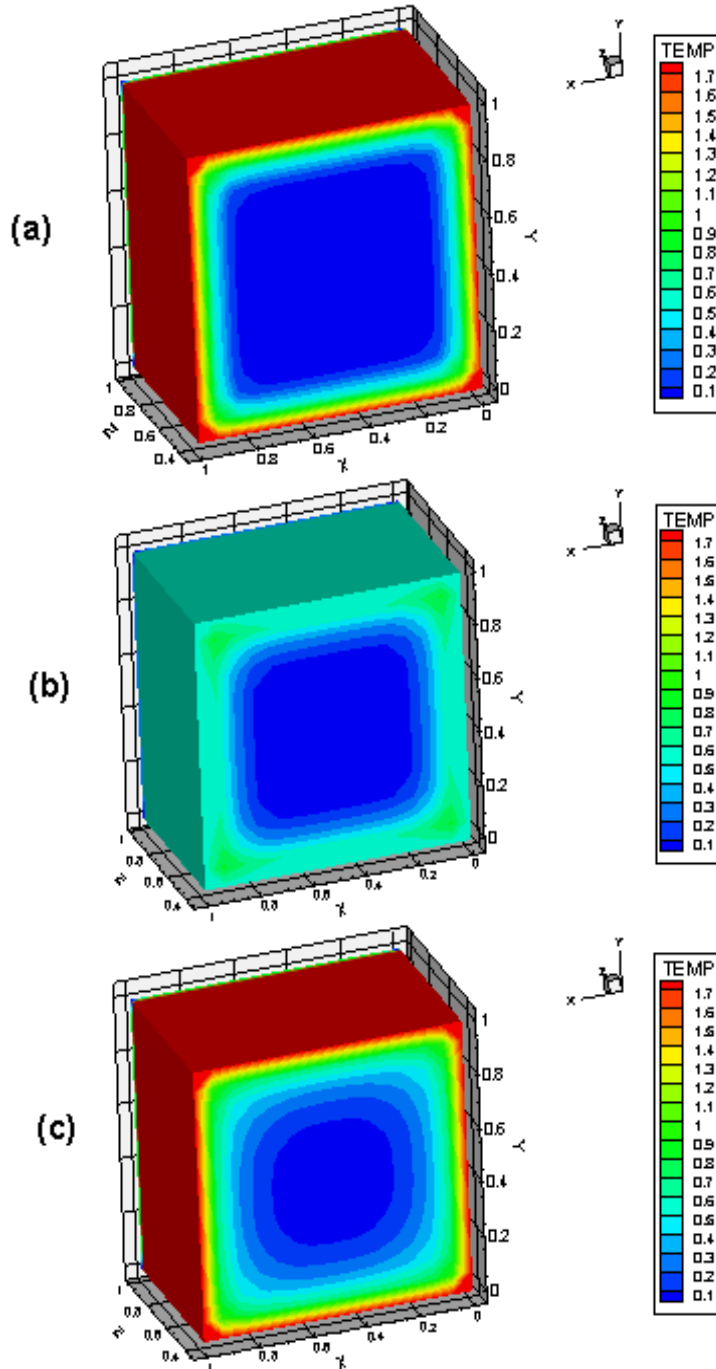
Fig. (4): Three Dimensional Transient Temperature Distribution at Section (z=0.35) for Ra=150, (a) t=0.003, (b) t=0.006, (c) t=0.012

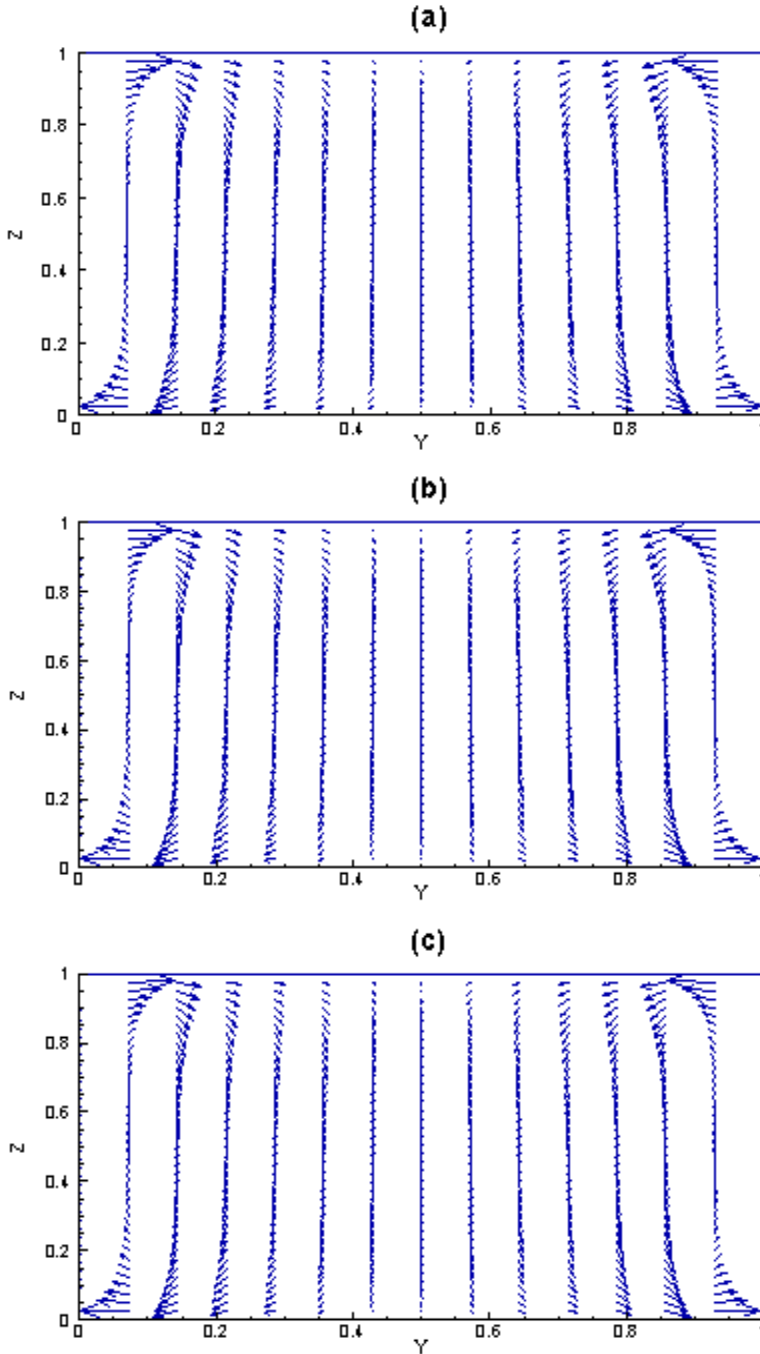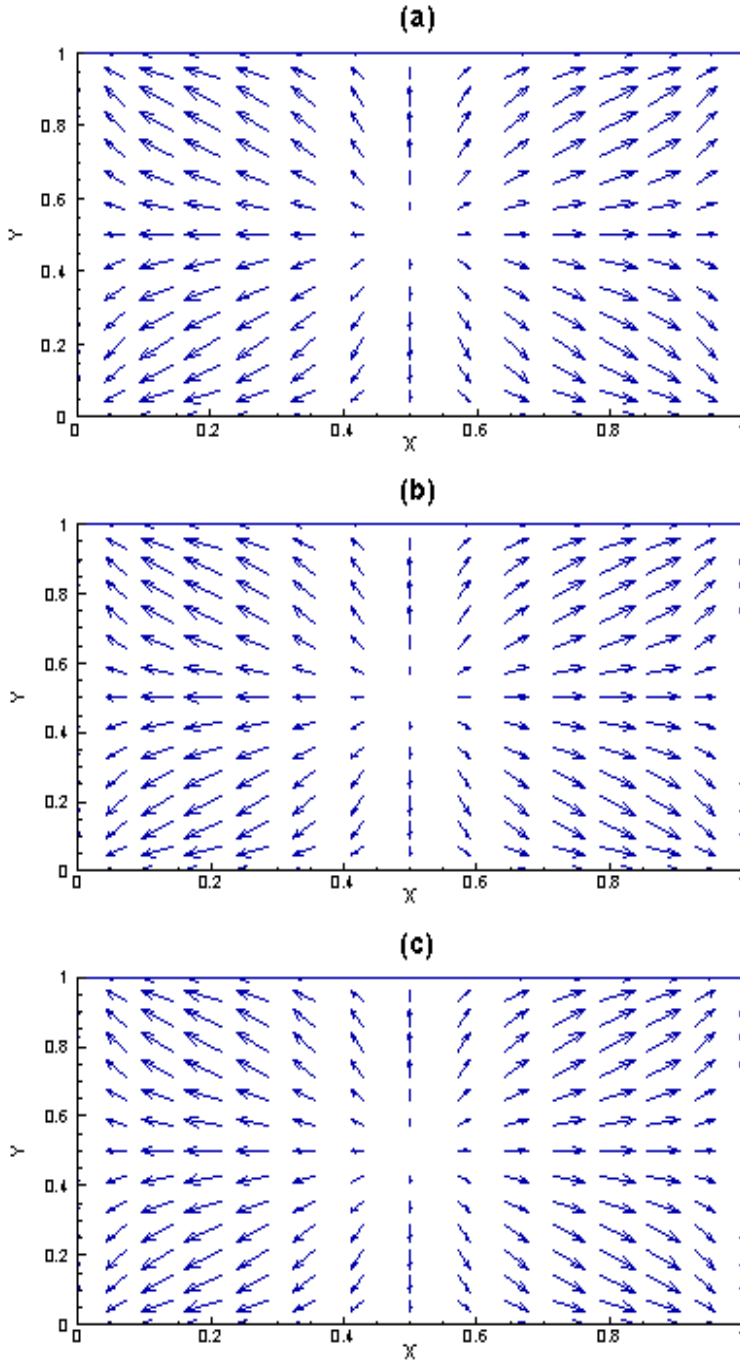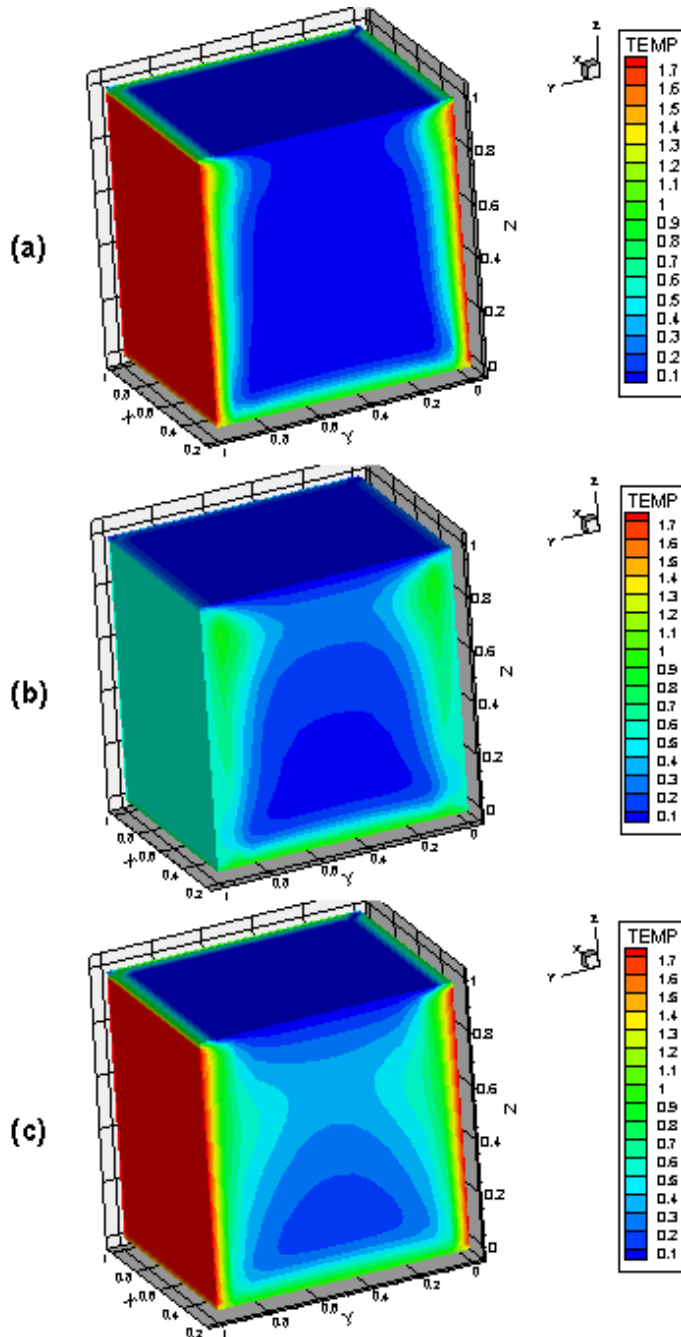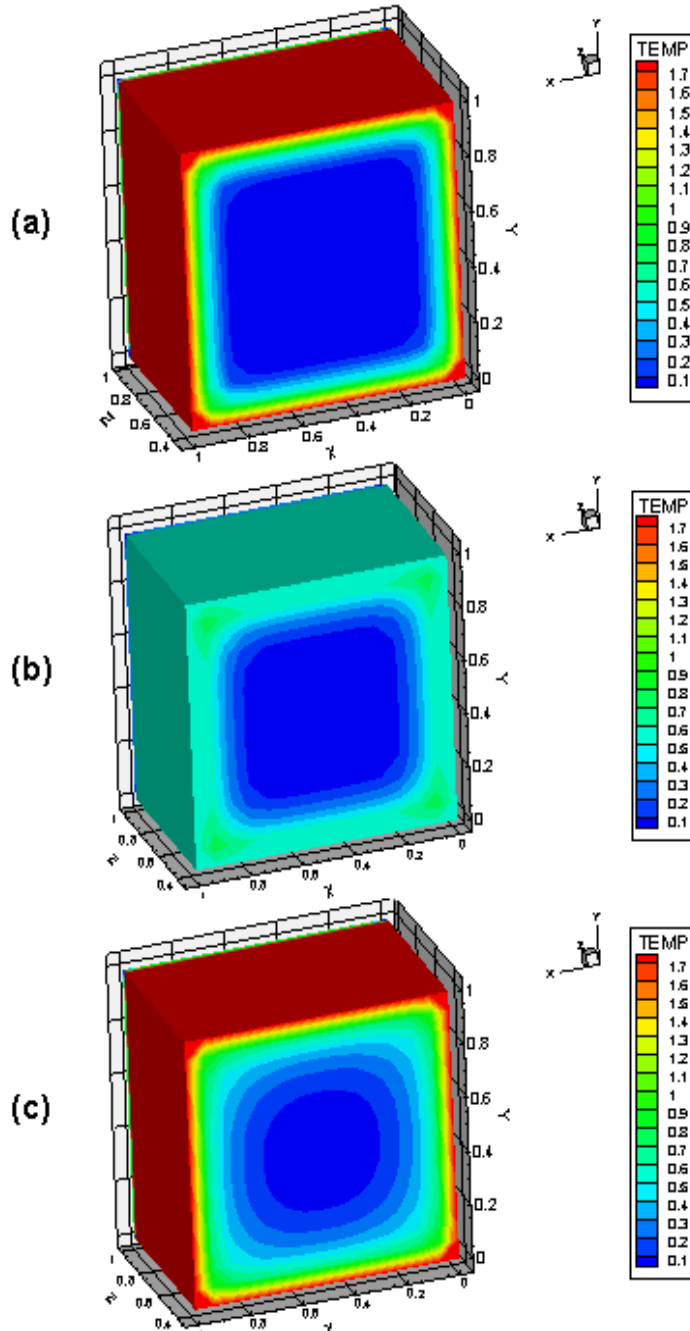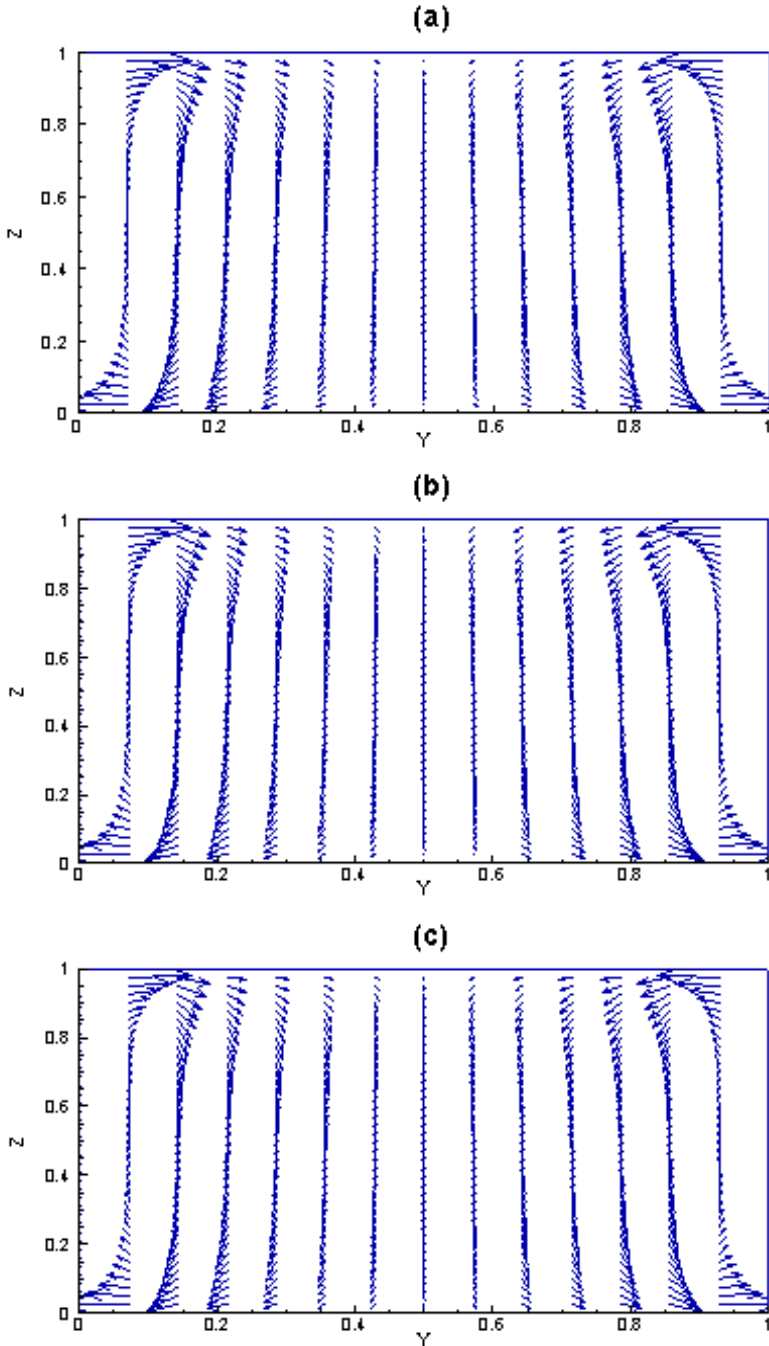**Fig. (5): Velocity Distribution at x=0.214 for Ra=150, (a) t=0.003, (b) t=0.006, (c) t=0.012**

Fig. (6): Velocity Distribution at z=0.3 for Ra=150, (a) t=0.003, (b) t=0.006, (c) t=0.012

Fig. (7): Three Dimensional Transient Temperature Distribution at Section (x=0.214) for Ra=200, (a) t=0.003, (b) t=0.006, (c) t=0.012

Fig. (8): Three Dimensional Transient Temperature Distribution at Section (z=0.35) for Ra=200, (a) t=0.003, (b) t=0.006, (c) t=0.012

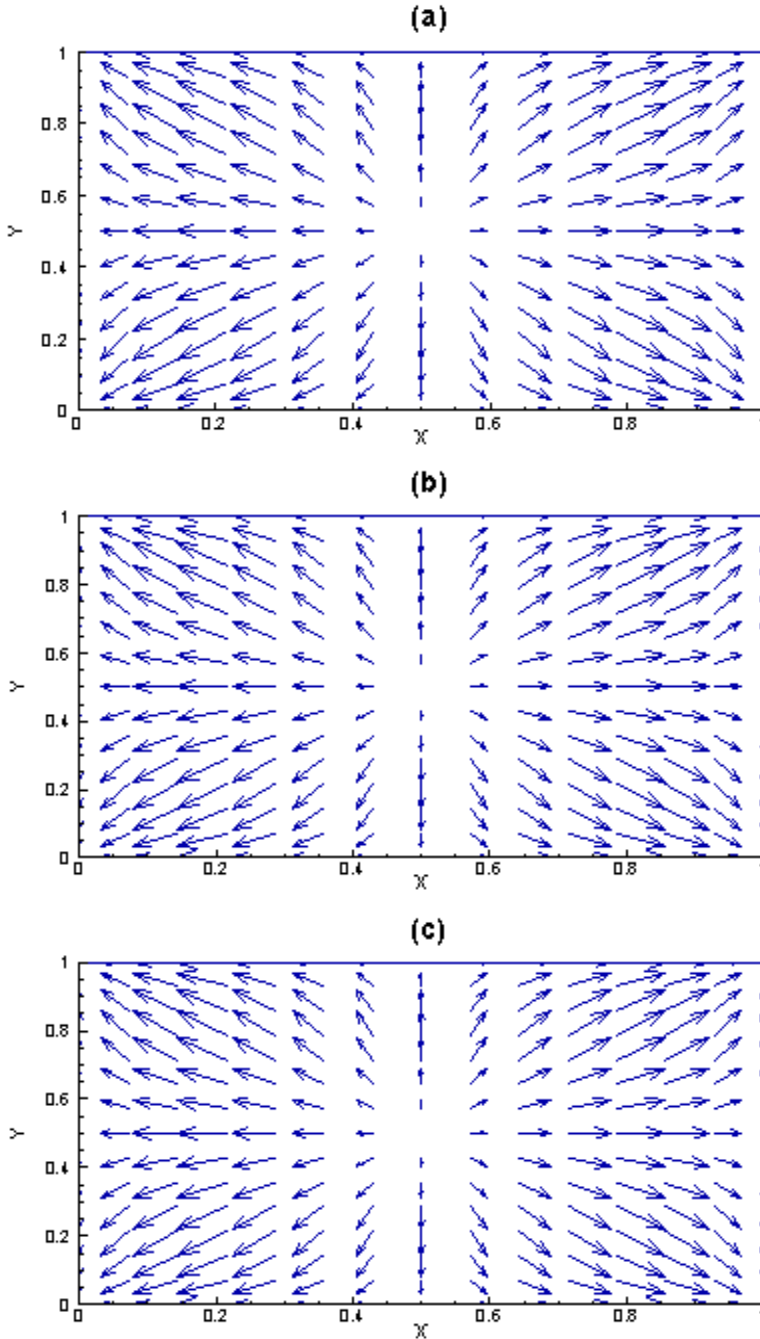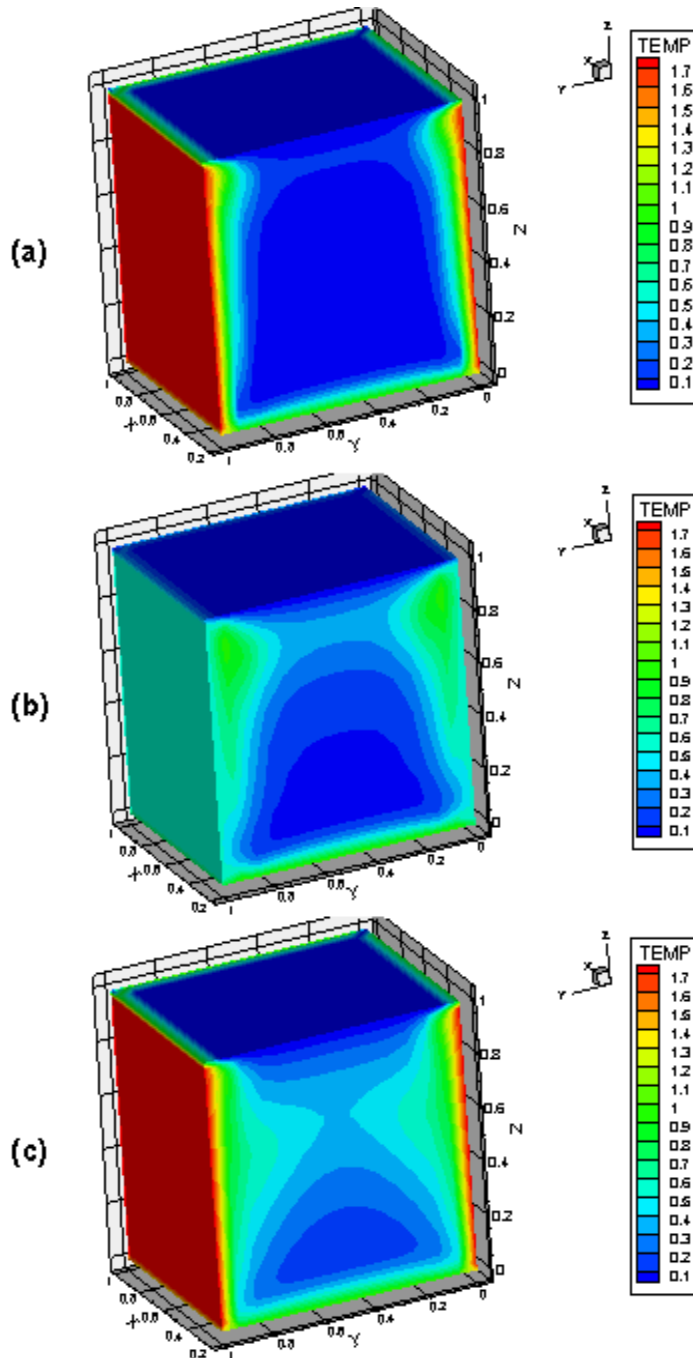**Fig. (9): Velocity Distribution at x=0.214 for Ra=200, (a) t=0.003, (b) t=0.006, (c) t=0.012**

Fig. (10): Velocity Distribution at z=0.35 for Ra=200, (a) t=0.003, (b) t=0.006, (c) t=0.012

Fig. (11): Three Dimensional Transient Temperature Distribution at Section (x=0.214) for Ra=250, (a) t=0.003, (b) t=0.006, (c) t=0.012
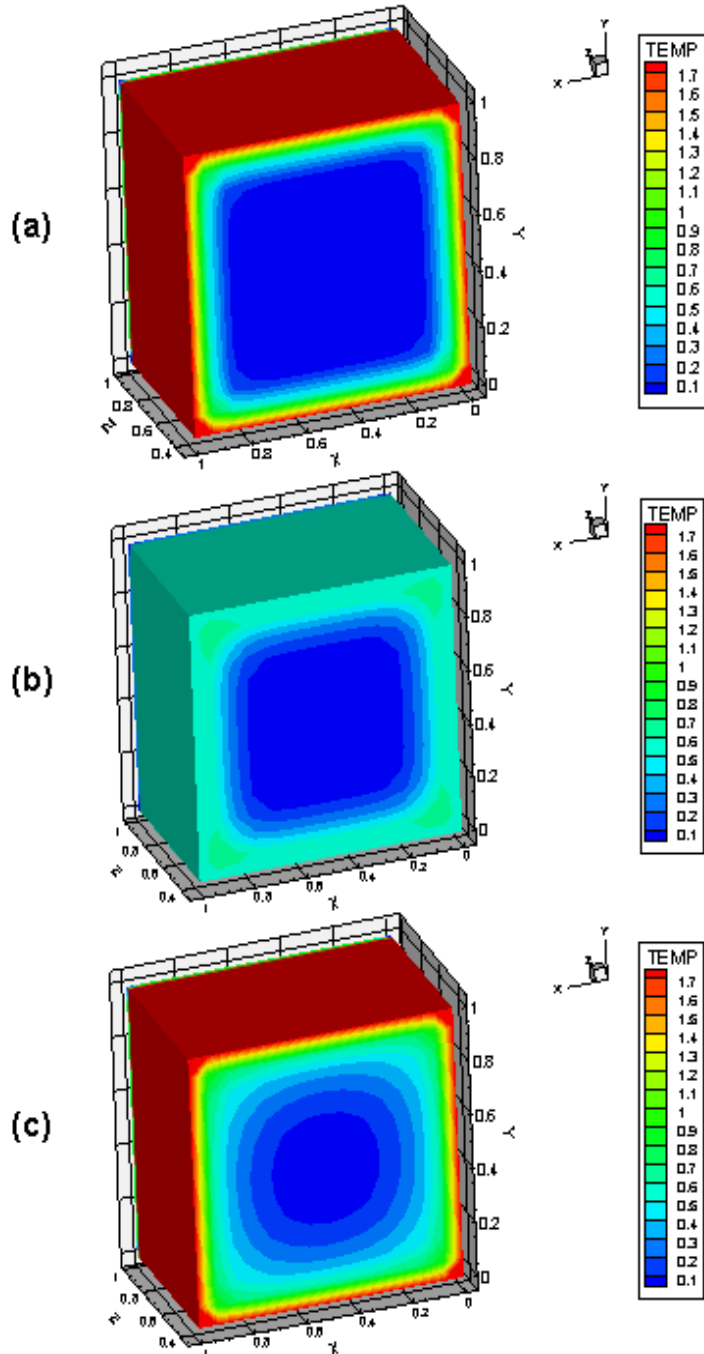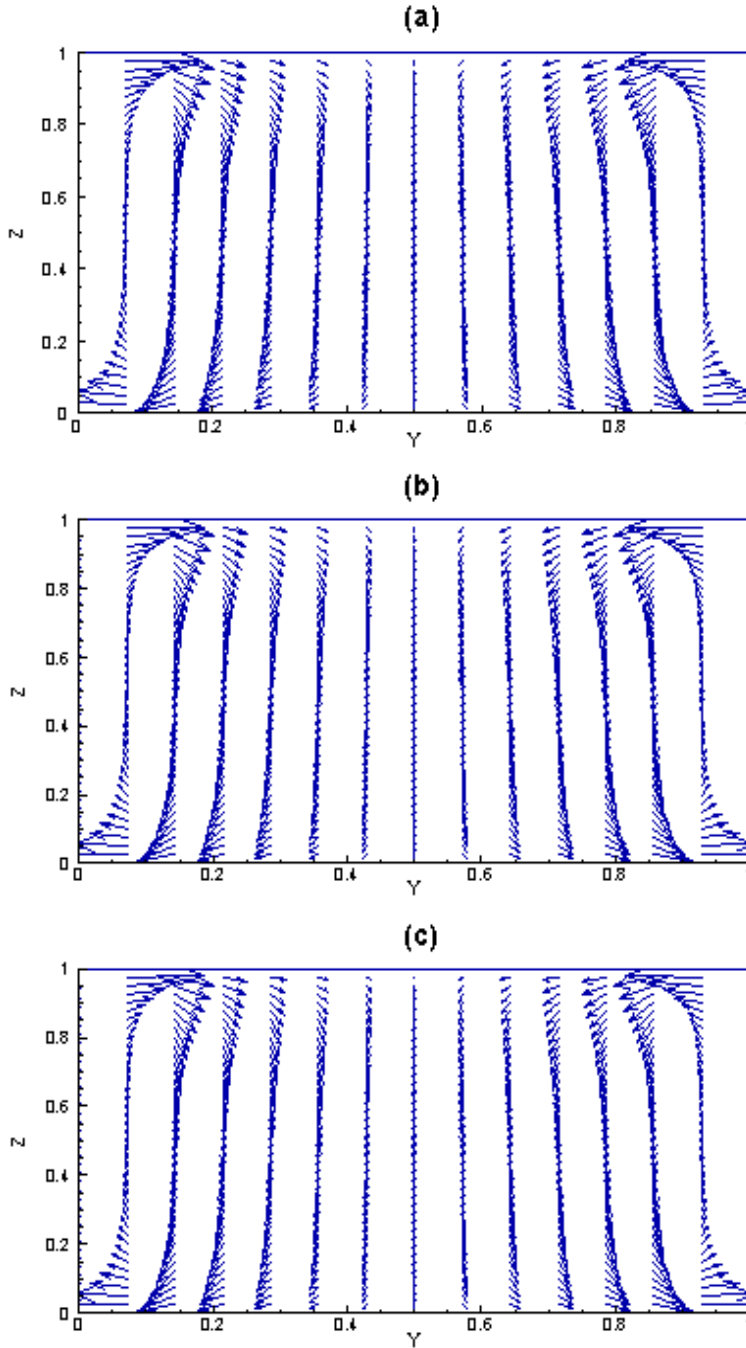
Fig. (12): Three Dimensional Transient Temperature Distribution at Section (z=0.35) for Ra=250, (a) t=0.003, (b) t=0.006, (c) t=0.012

**Fig. (13): Velocity Distribution at x=0.214 for Ra=250,
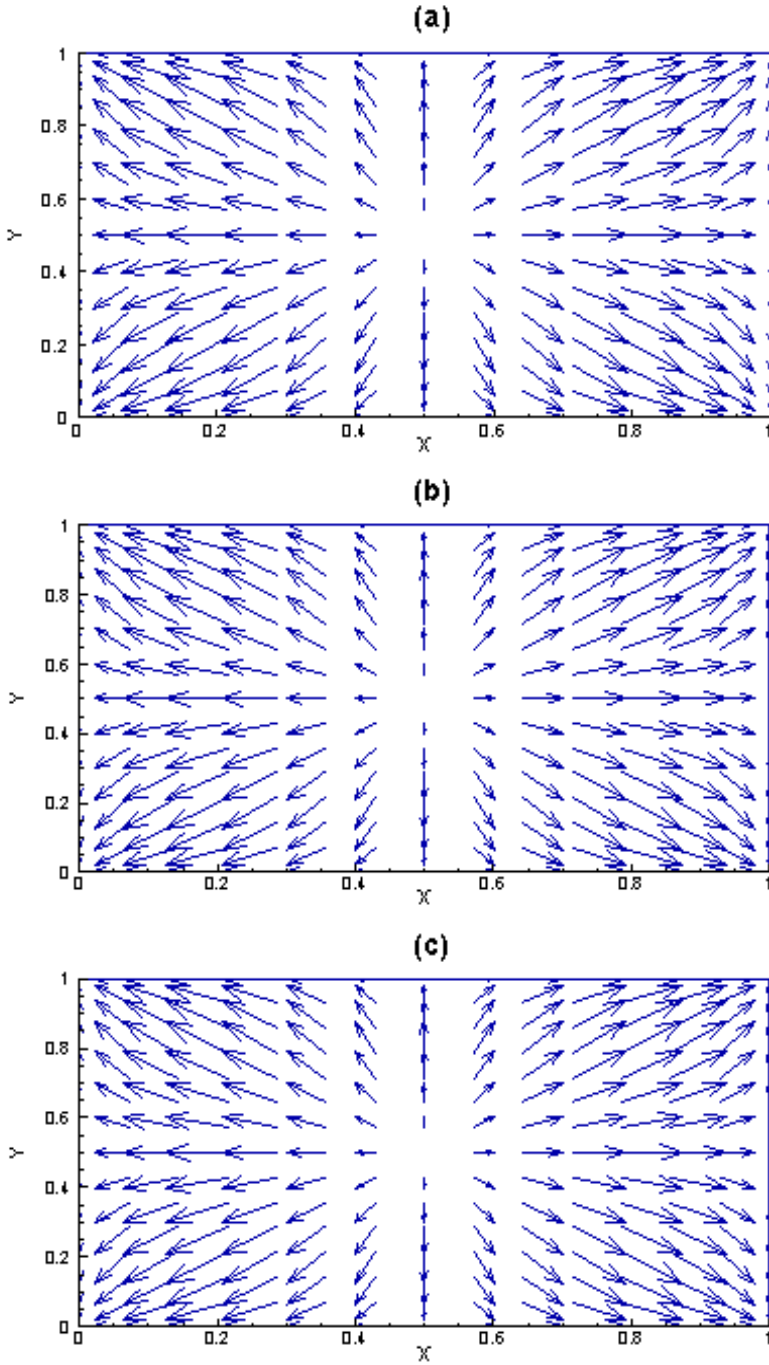(a) t=0.003, (b) t=0.006, (c) t=0.012**

Fig. (14): Velocity Distribution at z=0.35 for Ra=250, (a) t=0.003, (b) t=0.006, (c) t=0.012

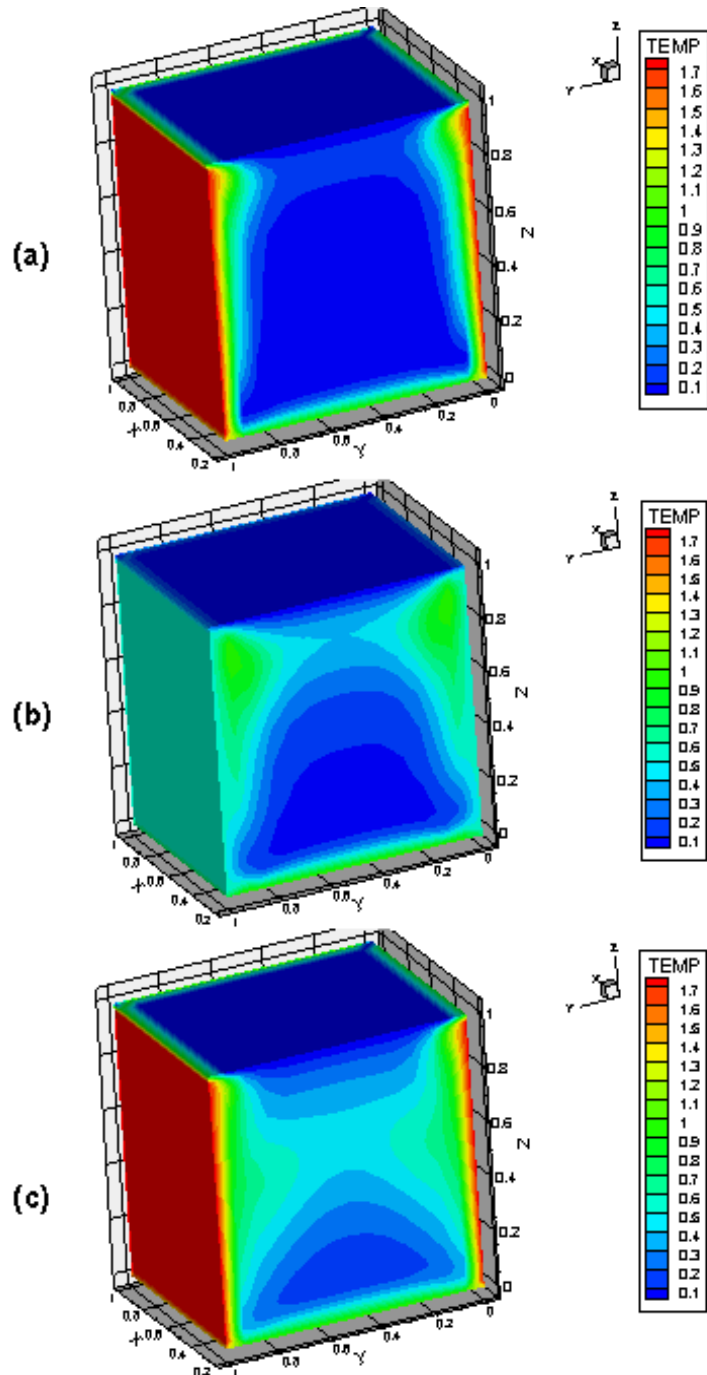**Fig. (15): Three Dimensional Transient Temperature Distribution at Section (x=0.214) for Ra=300, (a) t=0.003, (b) t=0.006, (c) t=0.012**
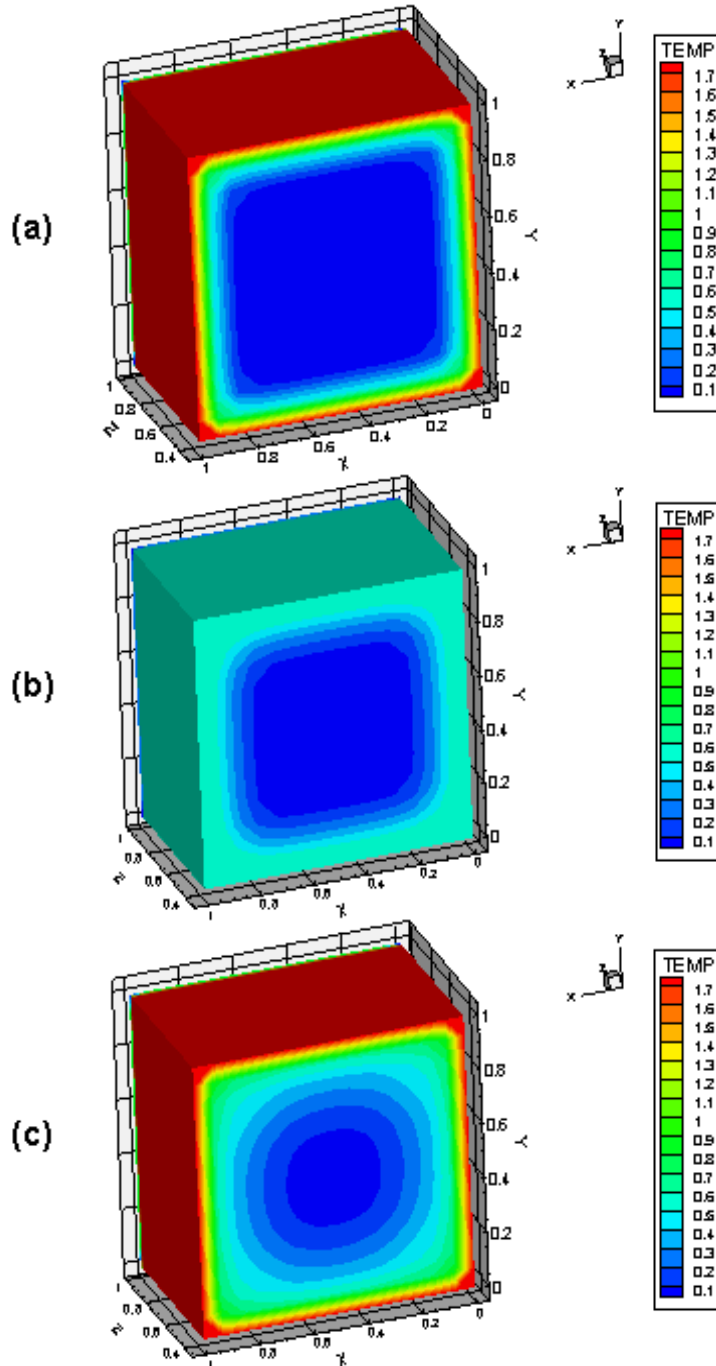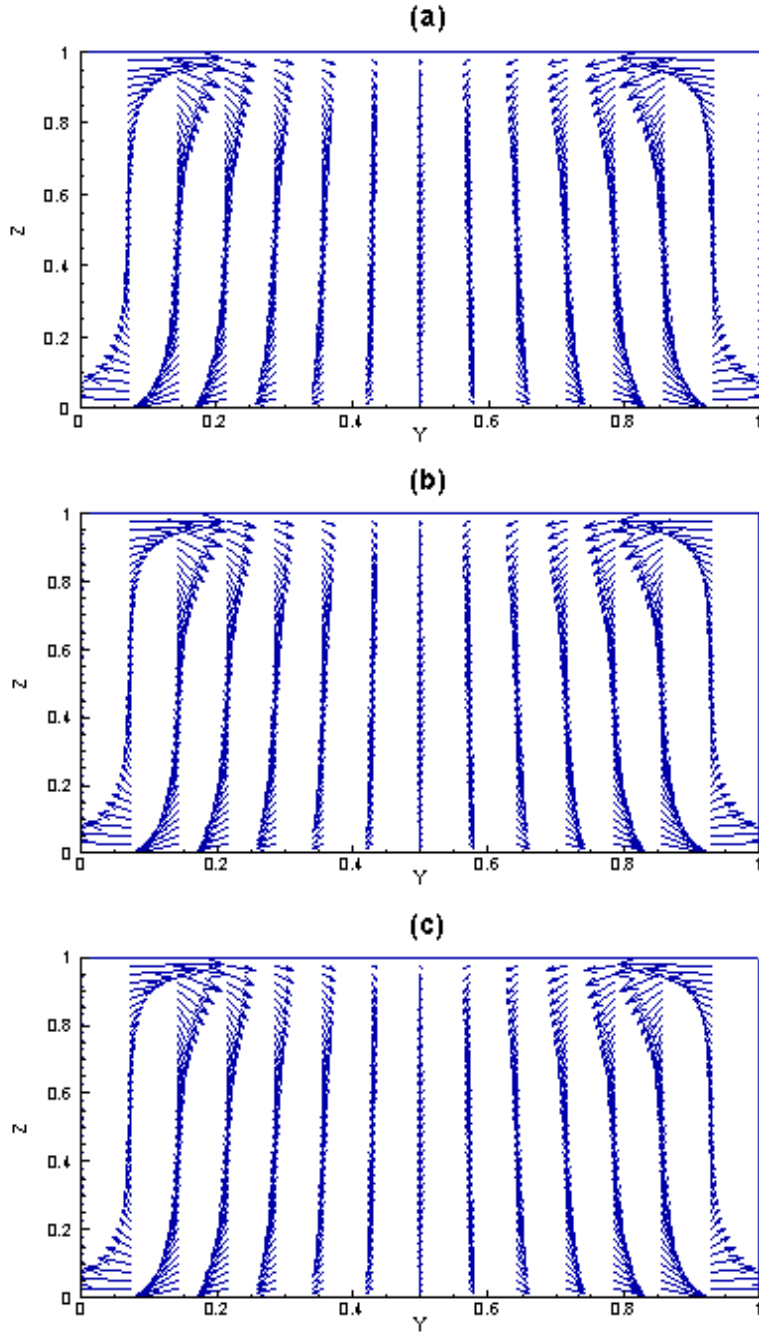
Fig. (16): Three Dimensional Transient Temperature Distribution at Section (z=0.35) for Ra=300, (a) t=0.003, (b) t=0.006, (c) t=0.012

**Fig. (17): Velocity Distribution at x=0.214 for Ra=300,
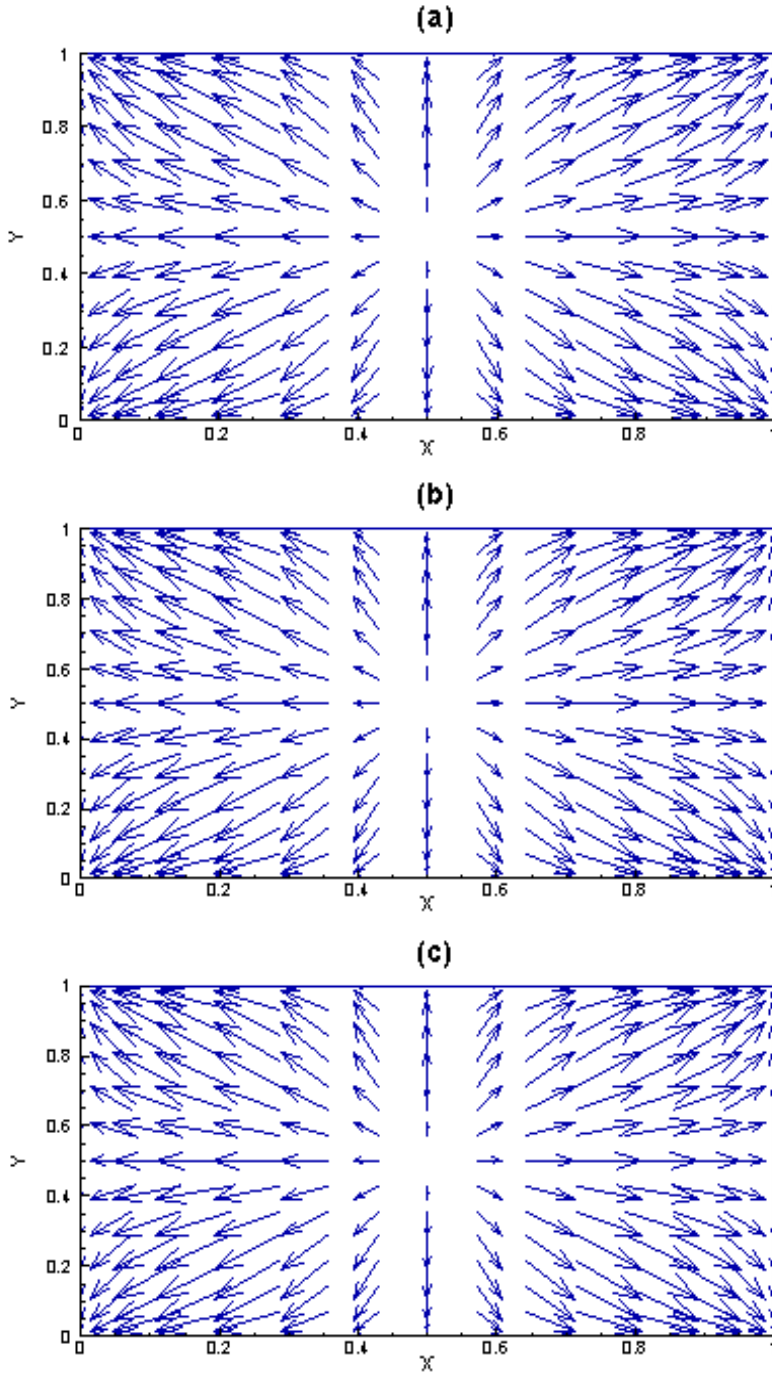(a) t=0.003, (b) t=0.006, (c) t=0.012**

Fig. (18): Velocity Distribution at z=0.35 for Ra=300, (a) t=0.003, (b) t=0.006, (c) t=0.012
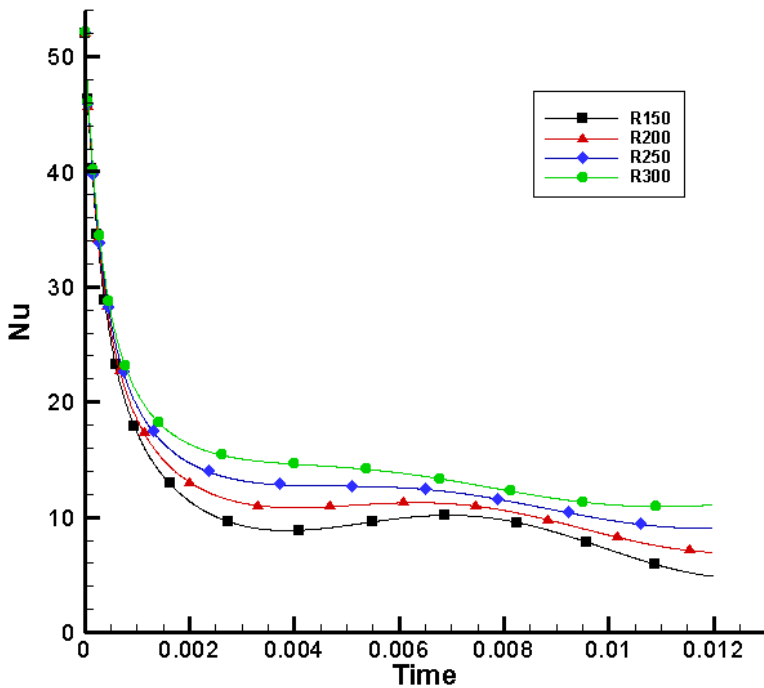
Fig.(19): Variation of Nusselt Number with Time for Various Values of Rayleigh Number

4. Conclusions

Unsteady natural convection in a box of fluid-saturated porous medium heated from below, cooled from above and time-periodic temperature variation at all vertical sides have been studied numerically. The periodic flow field consists of two cells of equal size formed by the ascending and descending flows rotating in opposite direction. The isothermal lines are curvilinear in shape indicating vigorous convective flow in the model.The Nusselt number varies inversely with time, it decreases when the time is increased and this relation takes a curvilinear nature in its shape. Also, Nu varies directly with Ra and therefore it increases when the Rayleigh number is increased.

NOMENCLATURE

SYMBOL	DESCRIPTION	UNIT
A'	Amplitude	$^\circ$C
a	Dimensionless amplitude	-
g	Acceleration Due to Gravity	m/s^2
K	Permeability	m^2
k_f	Thermal Conductivity of the Fluid	W/m.$^\circ$C
k_m	Effective Thermal Conductivity of the Porous Medium	W/m.$^\circ$C
Lx	Length of Box in x-Dir.	m
Ly	Length of Box in y-Dir.	m
Lz	Length of Box in z-Dir.	m
Nu	Nusselt Number	-
p	Dimensionless Pressure	-
p'	Pressure	N/m^2
Ra	Rayleigh Number	-
Ra_c	Critical Rayleigh Number	-
T	Dimensionless Temperature	-
T_o	Reference Temperature	$^\circ$C
T'	Temperature	$^\circ$C
Th'	Hot Wall Temperature	$^\circ$C
$\bar{T}h'$	Mean Hot Wall Temperature	$^\circ$C
t	Dimensionless Time	-
t'	Time	s
u	Dimensionless Component of Velocity in x-Dir.	-
u'	Component of Velocity in x-Dir.	m/s
v	Dimensionless Component of Velocity in y-Dir.	-
v'	Component of Velocity in y-Dir.	m/s
w	Dimensionless Component of Velocity in z-Dir.	-
w'	Component of Velocity in z-Dir.	m/s
x	Dimensionless Length in x-Dir.	-
x'	Length in x-Dir.	m
y	Dimensionless Length in y-Dir.	-

y'	Length in y-Dir.	m
z	Dimensionless Length in z-Dir.	-
z'	Length in z-Dir.	m
α_m	Thermal Diffusivity of the Porous Medium	m^2/s
β	Volume Coefficient of Expansion	1/ K
υ	Velocity Vector	-
ϕ	Vector Potential	-
ϕ_x, ϕ_y, ϕ_z	Vector Potential Component in x,y and z Dir. Respectively	-
μ	Dynamic Viscosity	kg /m.s
ν_f	Kinematic Viscosity of the Fluid	m^2/s
θ	Angle of Inclination	deg
ρ	Density	kg /m^3
ρ_f	Fluid Density	kg /m^3
τ	Dimensionless Period	-
τ'	Period	s

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الحمل الحر الأنتقالي الثلاثي الأبعاد في وسط مسامي مع ظروف حدية متغيرة مع الزمن

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المستخلص:

تم في هذا البحث دراسة عددية للحمل الحر الأنتقالي الثلاثي الأبعاد في وسط مسامي محدد ومشبع بالمائع. الشكل قيد الدراسة كان عبارة عن صندوق ذات درجة حرارة متغيرة دوريا مع الزمن من الجوانب وبدرجة حرارة ثابتة عند سطحه العلوي والسفلي. شمل التحليل العددي تحويل معادلة الزخم لجريان المائع خلال الوسط المسامي الى معادلة بدلالة جهد المتجه والتي بدورها حلت بأستخدام طريقة التكرار المفرط التراخي بينما تم حل معادلة الطاقة بواسطة الطريقة الضمنية المتناوبة الأتجاه. أن قيم أعداد رالي قيد البحث كانت (300,250,200,150). تم عرض النتائج على شكل خرائط كنتورية بالنسبة لدرجات الحرارة وخرائط متجهات سرع بالنسبة للسرعة. أظهرت النتائج العددية زيادة في درجة الحرارة داخل الصندوق عند أزدياد الوقت أو عدد رالي كما أن تغير عدد نسلت كان تغيرا عكسيا مع الزمن بينما يزداد بزيادة عدد رالي. تم أستنتاج نمط ثنائي الخلية في المستوي (y-z) .

Key Wards: transient, three-dimensional, natural convection, porous.