Free Convection in a Porous Wavy Chamber with Non-Uniform Side Wall

Govindarao Nammi[a], Sampatrao Ritesh Neelkanth Raju [a], Pogiri Ajay Kumar[a], Rayi Naveen[a], Vasireddy Venkatesh[a], Tangudubilli Ajay Manikanta[a], Penta Manikanta[a]

[a] Department of Mechanical Engineering, GMR Institute of Technology, Rajam, 532127, India

*Corresponding Author. Tel +91 8403978868

E-mail address :govvind3578@gmail.com

Abstract

A numerical investigation on free convection in a porous wavy chamber with non-uniform side wall will be conducted, with findings for various Rayleigh numbers and various porosity of the medium. Here, Rayleigh number changes from $10^3 \leq Ra \leq 10^6$ and porosity of the medium used can be changed through Darcy number$10^{-4} \leq Da \leq 10^{-2}$. Streamlineand isotherm plotswill be monitored for changes. In this project, an enclosed square porous chamber with thermally insulated walls and unusual side wall is studied.heat transfer rate is calculated for three different cases: case 1 is a flat wall, case 2 is a sinusoidal side wall and Case 3 is a zig zag side wall, the rate of heat transfer is calculated based on the number of undulation (d=0,1,2,3) of the side wall. All of the cases will be compared to see which has the best heat transfer rate.

Keywords: Free convection, Enclosure, Porous media, Nusselt number, non-uniform, heat transfer.

Nomenclature

g	Acceleration due to gravity, m.s^{-2}
Ra	Rayleigh number
Da	Darcy number
k	Thermal conductivity, W.m^{-1}K^{-1}
T_h	Temperature of hot wall
T_c	Temperature of cold wall
Nu_t	Averaged Nusselt number
L	Length of square enclosure, m
p	Pressure, N/m^2
Pr	Prandtl number
t	Time, s
$P*$	Non-dimensional pressure
T	Temperature, K
u	Velocity component in x direction, m.s^{-1}
v	Velocity component iny direction, m.s^{-1}
$U*$, $V*$	Non-dimensional velocity components
$X*$, $Y*$	Non-dimensional Cartesian coordinates
x, y	Cartesian coordinates, m
$\theta*$	non-dimensional temperature
α	Thermal diffusivity,m^{2}s^{-1}
β	Thermal expansion coefficient, (1/K)
υ	Kinematic viscosity, m^2/s

1. Introduction

Natural convection is a free convection in which heat and mass transport mechanism takes place and flow of fluid generated solely by differences in density and temperature within the fluid. Natural convection is an important phenomena which occurs in many engineering applications and scientific fields like building design, electronics cooling , food, geophysical fluid dynamics and geo thermal systems . For designing successful heat transfer systems require good understanding of natural convection . Nowadays there are several published papers that are discussed on the topic of free convection through porous media. Mohsen Izadi et al.[1] studied on the free convection that effects hybrid nano fluid inside a porous medium. The results showed on this study are parameters of periodic magnetic field can have non-monotonic impact on performance of heat transfer. Additionally, different factors likeHartmann number, Rayleigh number, Periodicity of magnetic field, Darcy number, and medium porosity had an impact on flow and thermal patterns. A.S. Dogonchiet al.[2] investigated numerically by the method using control volume finite element method and observed that Rayleigh number and Darcy number has direct relation with vigorous convective flow while it has an inverse relation with the magnetic field's inclination angle of Hartmann number. B.PekmenGeridonmez and Hakn F. Oztop [3] has done research on the Natural convection in partially effected magnetic field in a cavity that is filled in unit square with porous medium and observed that partial magnetic field has an impact on the development of vortices and convective heat transport in porous media it was found that middle-centered magnetic fields can suppress convective heat transmission .Zehba A.S. Raizahet al.[4] analysed the free convection flow of v-shaped space with a nano-fluid filled within a diverse porous medium. The findings demonstrated that horizantal diverse porous media has the highest average Nusselt number where as similar porous media had the lowest rate of heat transmission. Omar Rafae Alomar et al.[5] studied convective heat transfer between two right angled plates enclosed in a square porous hollow by employing (LTNE) local thermal non equilibrium and non-Darcian flow assumption.

The study of the behaviour of materials containing interconnected void spaces, such as rocks, soils, biological tissues and manufactured materials is a fascinating and interdisciplinary area. Some flows that are moved by upthrust effects that may occur when steeping fluid flow of temperature is not uniform. These flows also known as free or natural convection movements that are influenced by density differences caused by temperature gradients and boundary conditions.Payam Gholamalipouret al.[6] has done numerical analysis on entropy production of cu-water nanofluid inside circular completely filled in presence of cylindrical heat source with a porous foam inside. Results showed that heat transfer can be bettered or collapsed by depending on the value of Rayleigh number, Darcy number and the direction of inner cylinder movement according to the various figures of eccentricity. Xiangjuan Yang et al.[7] analysed the free convection processes in three dimensions(3D) mixed porous medium and also connected with energy loss and mixing processes. The third dimension effect is used to compare the effect of convective Stream, Entropy production and heat transfer and observed that entropy variation indicators not changed in response to change in heterogeneity.T.R. Vijaybabu [8] has analysed the impact of a magnetic field in two different density gradients free convection. Entropy generation, which is measured using the lattice Boltzmann method and is done in enclosure.

It is a way of describing how useful energy is lost and how engineering systems such transport and rate processes degrade either time Lattice Boltzmann method is one of the method to solve the current numerical problem.This method has significant achievement in simulating fluid streams or fluid flows . They learned through the numerical analysis that the magnetic fields intensity and direction,buoyancy force and permeability of the porous cylinder combined may considerably control the heat, flow and concentration characteristics . M. Sheikholeslami and S.A. Shehzad et.al[9] shows the results on simulations in porous embedded with nanofluid convective stream by using two temperature models show that stream function maximum increases augment of nanofluid confluence heat transfer variable and porous media's porosity but stream function is inversely proportional to Hartman number. Dhananjay Yadav [10] explained the use of linear and non-linear stability analysis to determine how chemical reactions affect convective instability and heat transfer in nanofluid-saturated porous enclosures. The results demonstrate that for rectangular enclosures the amount of heat transmission increases with increasing heat capacity ratios, while it decreases with aspect ratio for slender and square enclosures results are opposite.

Fernando J. Guerrero et.al [11] has carried out impermanent simulations numerically to evaluate the heat transfer and convective mass in a void medium that is heated from below and salted from above and it is also subjected to an inclination angle. Focusing on a set of some governing variables and equations determined by two lightness ratios. The results provided are quantitative insights into how mixing improves as buoyancy forces increases. Most of the times FEM is used to solve the problems and determine the solutions. Finite element method (FEM) is mostly used method to solve differential equations that are arises in fields like mathematical modelling and engineering. it is mainly used to solve the problems those are associated with heat conduction, incompressible viscous flows and convective heat flow. S. Sivasankaran et. al [12] has done numerical study of non-Newtonian fluid in a porous embedded with heat radiation and irregular heating on convection. It is aimed to numerical simulation and explore the flows like laminar, incompressible, buoyant induced convection drift in the existence of heat radiation.Jayesh Subhash Chordiya and Ram VinoySharma[13] has studied on the free convection in a fluid-soaked void embedded with a couple of vertical diathermal separation . The results shows that partition ratio is inversely proportional to Nusselt number in porous enclosures. Seyyed Masoud Seyyedi [14] has studied on the behaviour of heat transfer in the cardioid structured porous activity. S.A. Shehzad [15] has recognised the impact of the heat transfer of unique inorganic nanomaterial inside an absorbant medium and used CVFEM method to obtain the outputs .the results were compared with the previous articles and concluded that by reducing the temperature and increasing the Rayleigh number gives better cooling performance for high buoyancy forces.

The widely spaced component of surface appearance is measured as waviness. Waviness is used to indicate abnormalities or changes in material surface on a millimetre to centimeter scale. waviness in particular can have substantial impact on a product functioning and performance.Ching-Chang Cho [16] studied on the effects of wavy surface and void medium on the free convection of copper water nanofluid and the creation of disorder in a squared space with a partially heated surface. The results shows that when Darcy number and Rayleigh number are high then mean Nusselt number and non-dimensional total entropy production is rises. When the Darcy number and Rayleigh numbers are rises then Bejan number is reduced. The conduction domination is the main reason for this outcomes. A. Sattar Dogonchiet.al[17] analysed the heat transfer using buoyancy-driven flow and entropy formation of nano liquid inside a porous enclosure employing two square cylinders is described in this paper. The results shows that higher fluid density differences are caused by a rise in the enclosure velocity gradient brought on by rising Rayleigh number, if Rayleigh number increases the rate of heat transmission may increases but as Hartman increases the reverse effect occurs. the formation entropy is slowed down by the presence of porous matrix. The wavy side walls in containers can interfere with fluids natural convection flow. The buoyant forces and the flow patterns may be affected by the waves and the ability to produce areas of greater and lower temperature. The flow will often tend to follow the walls outlines and could get more complicated as the waviness rises.

2. Physical Model

A square porous enclosure with side length L has been studied in this problem, where the top and bottom walls are insulated and the right-side wall is regarded non-uniform, the left side wall is considered cold wall T_c, while the right-side wall is considered hot wall T_h (Fig. 1). Three different cases have been considered, in case 1: the non-uniform wall is a flat wall with zero undulation. In case 2: the non-uniform wall is sinusoidal in nature with undulation (d = 1, 2, 3) and in case 3 : the non-uniform wall is zig zag in nature with undulation (d = 1, 2, 3).

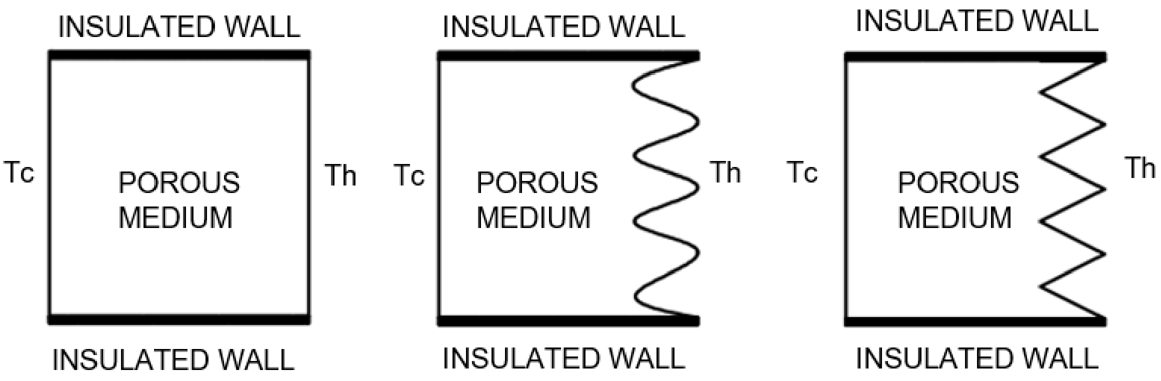


Fig 1: The physical model's schematic representation

2.1. Governing Equations:

Considering the flow within the enclosure as incompressible, 2 dimensional and laminar. The dimensionless governing equations such as momentum (*x* and *y*), energy conservation and mass can be stated as

$$\frac{\partial U^*}{\partial X^*} + \frac{\partial V^*}{\partial Y^*} = 0, \tag{1}$$

$$\frac{\partial U^*}{\partial t^*} + U^*\frac{\partial U^*}{\partial X^*} + V^*\frac{\partial U^*}{\partial Y^*} = -\frac{\partial P^*}{\partial X^*} + Pr\left(\frac{\partial^2 U^*}{\partial X^{*2}} + \frac{\partial^2 U^*}{\partial Y^{*2}}\right) - Pr\frac{U}{Da}, \tag{2}$$

$$\frac{\partial V^*}{\partial t^*} + U^*\frac{\partial V^*}{\partial X^*} + V^*\frac{\partial V^*}{\partial Y^*} = -\frac{\partial P^*}{\partial Y^*} + Pr\left(\frac{\partial^2 V^*}{\partial X^{*2}} + \frac{\partial^2 V^*}{\partial Y^{*2}}\right) - Pr\frac{V}{Da} + RaPr\theta^*, \tag{3}$$

$$\frac{\partial \theta^*}{\partial t^*} + U^*\frac{\partial \theta^*}{\partial X^*} + V^*\frac{\partial \theta^*}{\partial Y^*} = \left(\frac{\partial^2 \theta^*}{\partial X^{*2}} + \frac{\partial^2 \theta^*}{\partial Y^{*2}}\right). \tag{4}$$

The dimensionless parameters in the preceding equations are as follows:

$$X^* = \frac{x}{L},\ Y^* = \frac{y}{L},\ t^* = \frac{\alpha t}{L^2},\ U^* = \frac{uL}{\alpha},\ V^* = \frac{vL}{\alpha},\ P^* = \frac{pL^2}{\rho\alpha^2},\ \theta^* = \frac{T-T_c}{T_h-T_c},\ Da = \frac{k}{L^2},\ Pr = \frac{v}{\alpha},\ Ra = \frac{\beta g L^3 (T_h - T_c) Pr}{\upsilon^2},$$

where x and y are the horizontal and vertical Cartesian coordinates, and *u*is the velocity component in x-direction and v is the velocity component in y-direction along these coordinates. Respectively, Some of the parameters of the heat transfer are thermal diffusivity, thermal conductivity are denoted as α and *k*. other parameters like thermal expansion coefficient, permeability ,fluid density and momentum diffusivity are denoted as β,υ,*p*.respectively; Rayleigh, Prandtl, and Darcy numbers are denoted as Ra, Pr, and Da.

2.2. Boundary conditions:

The following are the boundary conditions for governing equations (1), (2), (3), and (4):

For hot side wall T_h:

$U^{*} = 0,\ V^{*} = 0,\ \theta^{*} = 1$ (5)

For cold side wall T_c:

$U^{□} = 0$, $V^{□} = 0$, $\theta^{□} = 0$ (6)

2.3. Initial considerations:

Throughout the domain, atmospheric pressure is used as a starting condition. The following are the other beginning conditions used in the simulation:

$U^{□} = 0$, $V^{□} = 0$ and $\theta^{□} = 0$ (7)

2.4. Nusselt number:

A dimensionless metric ,Nusselt number that measures convective movement rate of heat energy as bucked to diffusive movement, it is used to express therate of heat transfer. The average Nusselt number on the heated side wall is calculated as follows:

$Nu = hL / k$ (8)

$Nu_t = (1 / A) * \int (h(x)\, dx) / k$ (9)

3. Validation

We were validating the accuracy of the selected numerical approach used to solve the governing transfer equations prior to performing parametric numerical investigations.As a result, Govindarao nammi et.al. [19] examined similar parameters in his investigations for the porous cavity. The variations in Nut with respect to Ra for the number of undulations d=0 and taking Pr=0.7, Rayleigh number from 10^3 to 10^6, and Da=10^{-2} were compared. As shown in Fig. 2, the current numerical simulation findings are compared to those of Govindarao Nammi et.al.[19].

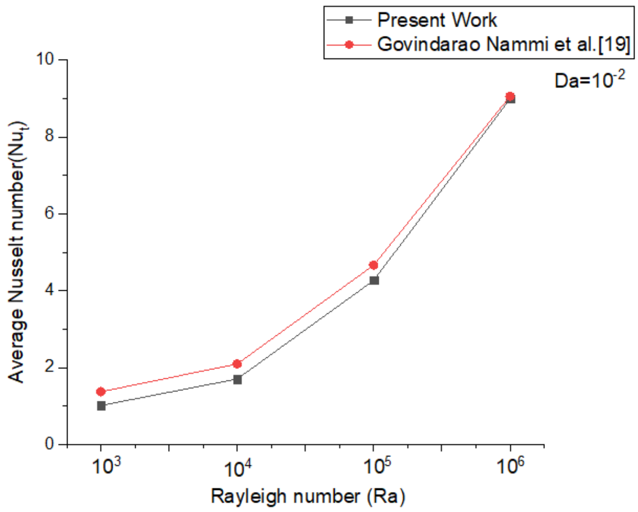


Fig 2. Average Nusselt number (Nu_t) variation w.r.t Rayleigh number Ra=10^3 to 10^6 at Darcy number 10^{-2}

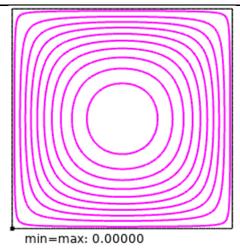
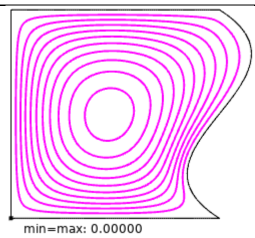
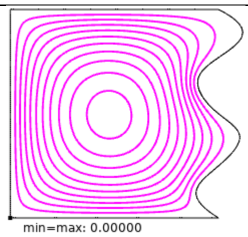
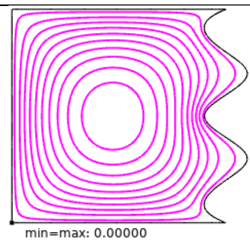
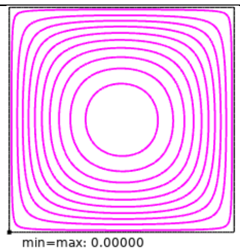
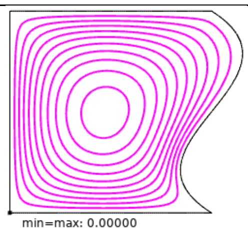
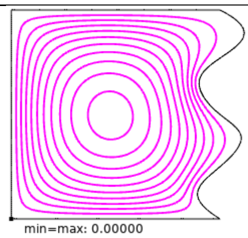
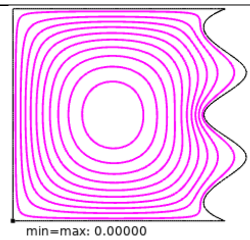
4. Results and discussions

The current research looks on buoyancy-induced thermal transport in a square porous enclosure with unusual side wall. The right side wall is a non-uniform side wall with undulation (d = 0, 1, 2, 3) and is referred to as the hot wall T_h, whereas the left side wall is referred to as the cold wall T_c, and the top and bottom walls are insulated. For each undulations calculations were accomplished for the values$10^{-4} \leq Da \leq 10^{-2}$ and$10^3 \leq Ra \leq 10^6$. The outcomes of the investigation are presented in 4.1 Streamlines and isotherm plots, 4.2 Nusselt number. temperature fields and flow designs are represented by streamline, isotherm plots as well as by an average Nusselt number expressing heat transfer from a non-uniform side wall.

4.1. Streamline and isotherm plots:

The effects of the medium's porosity and the non-uniform side wall on the flow and temperature fields are illustrated using streamlines and isotherms. The highly symmetric structure of streamlines and isotherms about both the horizontal and vertical axes for all undulations and Darcy numbers observed indicates that conduction dominates over convection in the enclosure at Ra = 10^3. The streamlines and isotherms plot for Da = 10^{-4} for varied Rayleigh numbers and undulations of sinusoidal and zigzag wall cases are shown in Figures 3, 4, 9 and 10. Conduction suppresses the convection mode at Da = 10^{-4}, even at large Rayleigh numbers.From Ra = 10^3 to 10^5, the streamlines and isotherms are nearly symmetrical, and at Ra = 10^6, minor convection currents are observed in both cases. Convection currents form at Da = 10^{-3} in both cases as a result of the associated influence by increasing buoyancy forces and Darcy number . (observe Figures 5, 6, 11, and 12). As the Darcy number is raised to Da = 10^{-3}, resistance of the flow decreases and fluid flowsthrew the voids, resulting in enhancedupthrust .As a result, when compared to Da = 10^{-4}, circulating cells are somewhat distorted.

The streamline and isotherm plots at Da = 10^{-2} for different Rayleigh numbers and undulations of sinusoidal and zigzag side wall cases are shown in Figures 7, 8, 13 and 14. Because of the combined effect of high Rayleigh and increased porosity at Da = 10^{-2}, the convection method of heat transmission becomes more prominent when the Ra value rises from 10^3 to 10^6.When compared to the flat side wall case with zero undulation, the non-uniform wall pattern causes the fluid flow to become more chaotic. Because the wall pattern creates vortices and secondary flows, which mix the fluid more effectively.Circulating cylinders form in the centreline at Ra = 10^6 as the undulation increases. At d = 1, one cell forms at the right side wall, and when the undulation increases to d = 2 and 3, two circulating cylinders form in the enclosure's centreline. According to the isotherm plot, when the Rayleigh number increases, the temperature gradients appear to become more intense, indicating higher convective heat transfer. Convection becomes stronger at Ra = 10^6 and Da = 10^{-2}, resulting in more distorted isotherms and streamlines.

	d= 0	**d= 1**	**d= 2**	**d= 3**
R_a=10^3				
R_a=10^4				

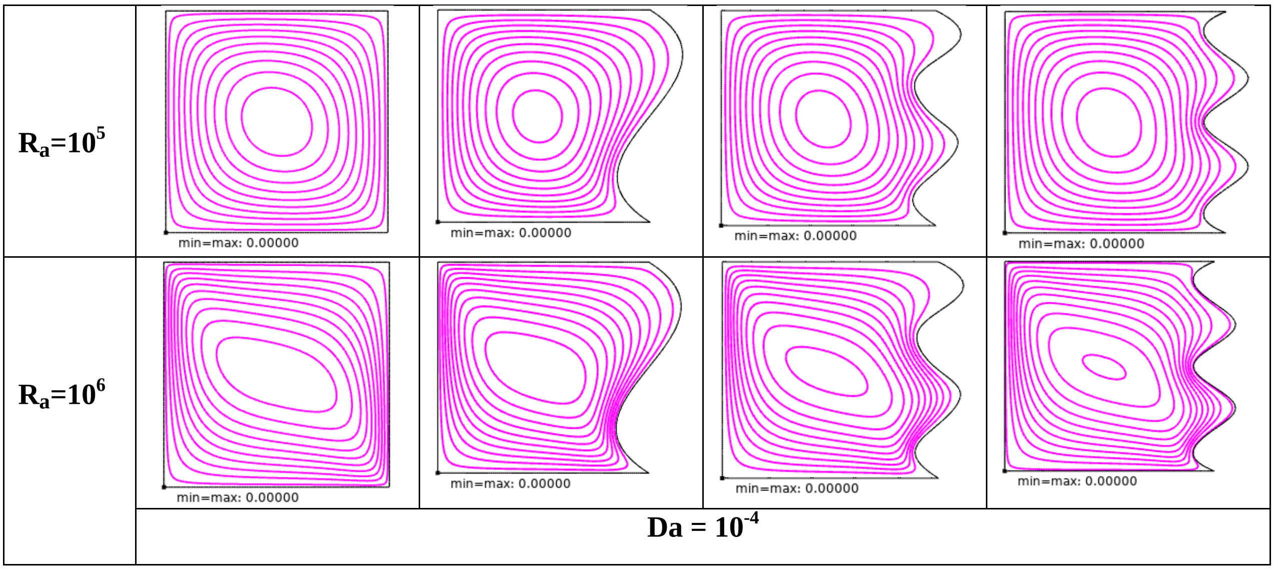


Fig 3. Streamlines at Darcy number Da=10^{-4} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$ sinusoidal wall case.

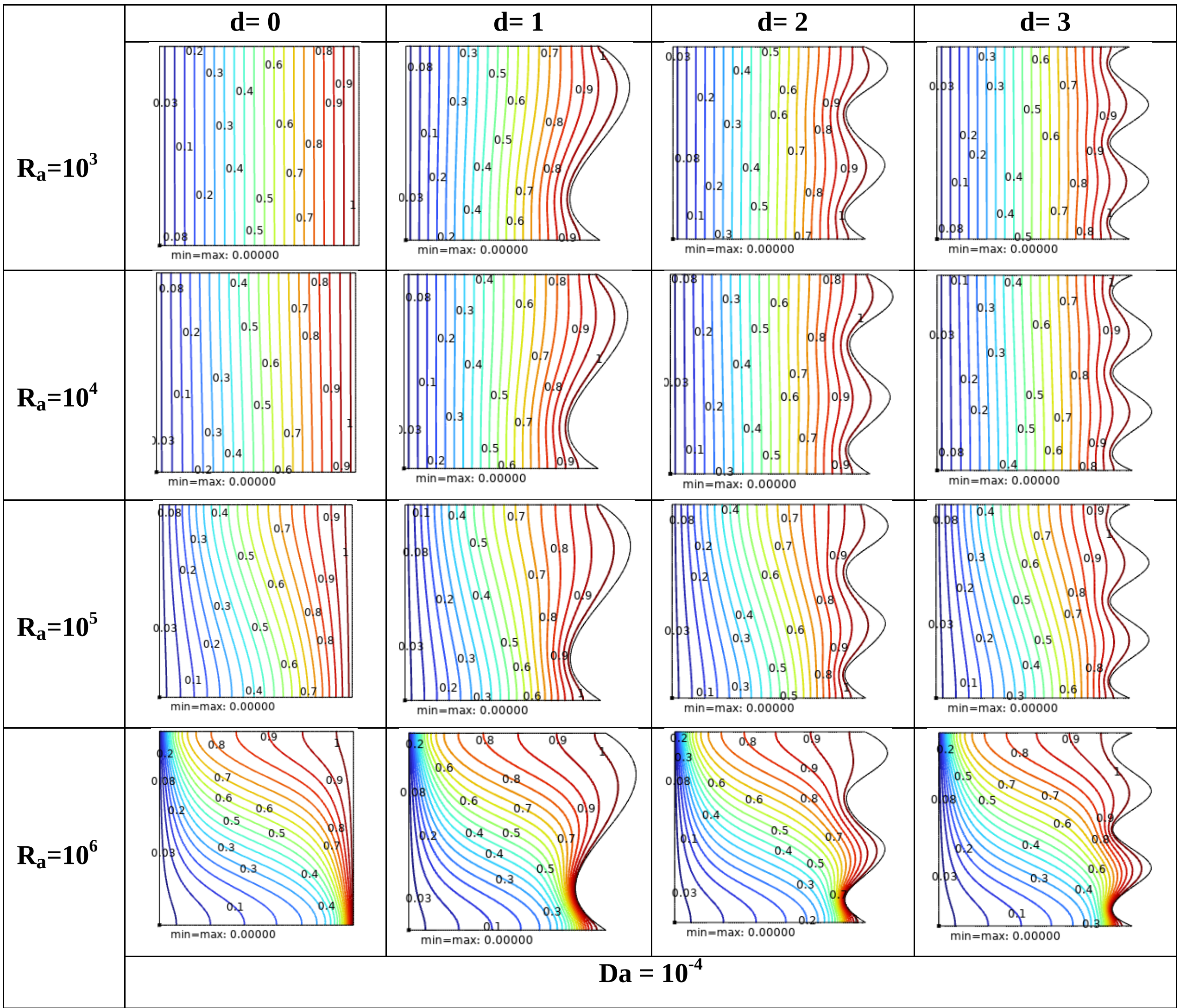


Fig 4. Isotherms at Darcy number Da=10^{-4} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$sinusoidal wall case.

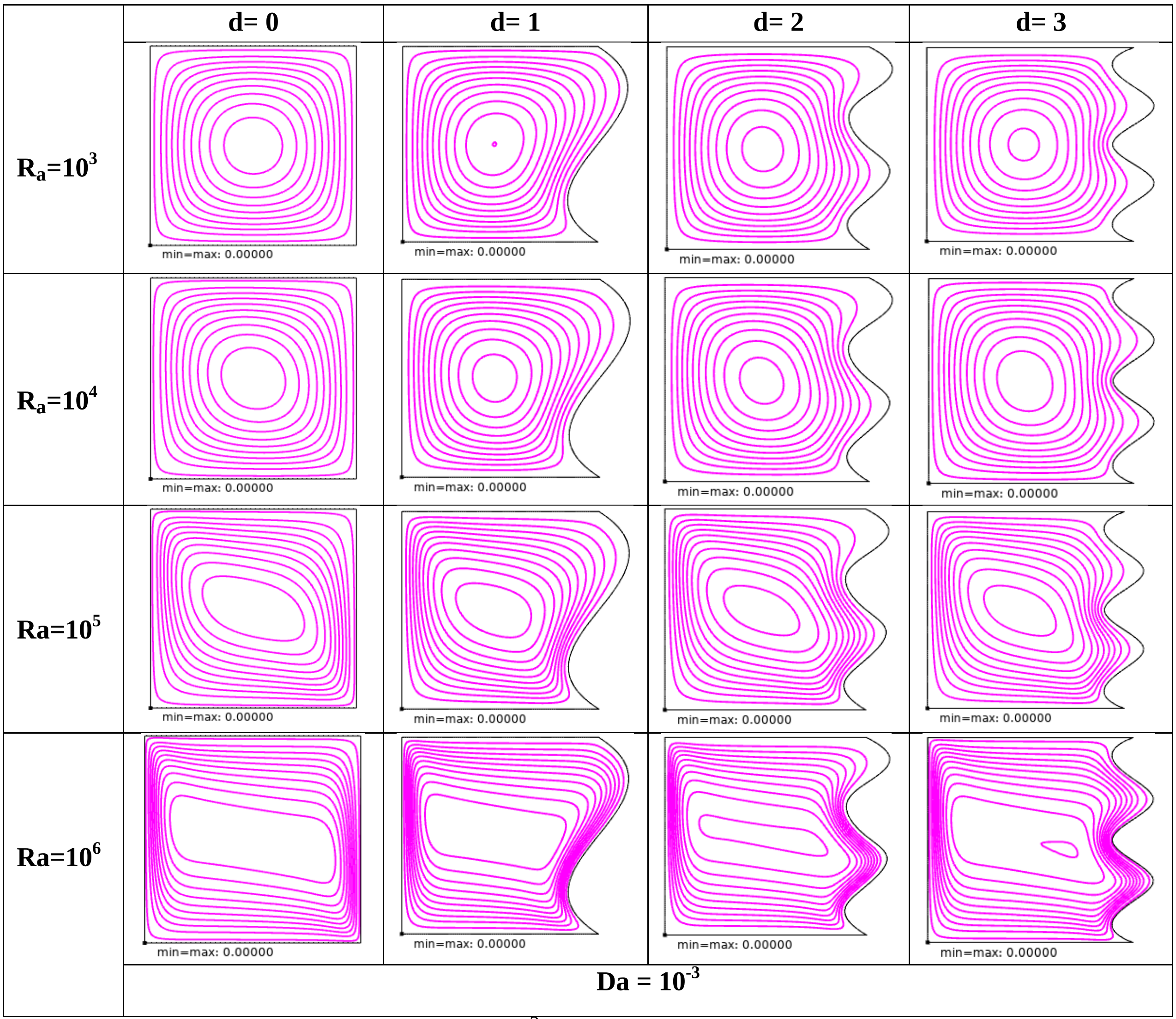
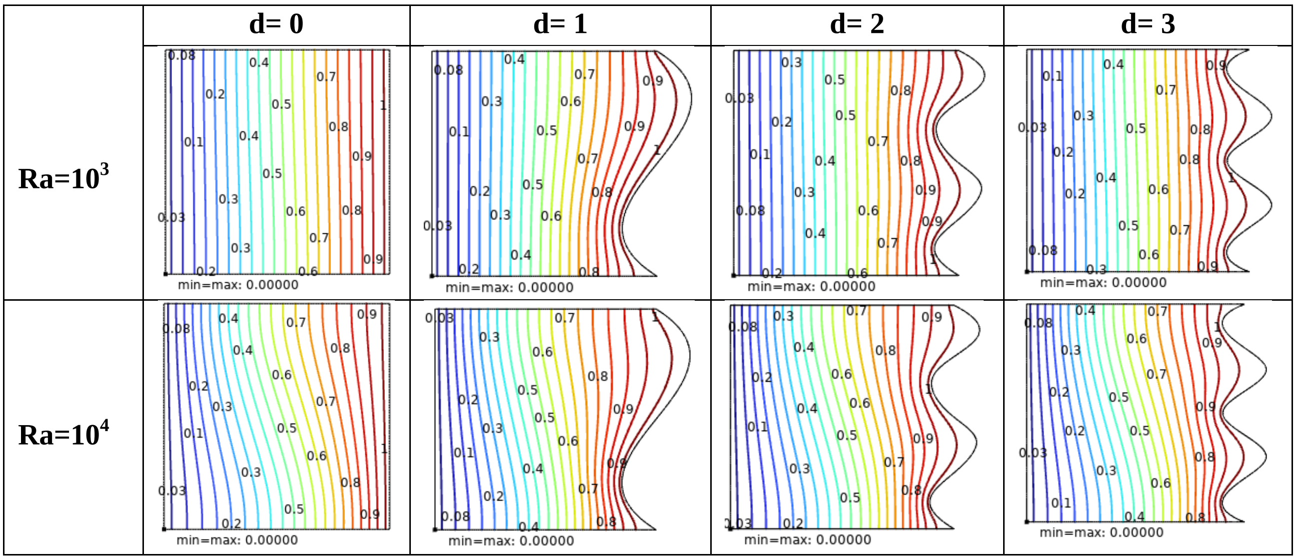


Fig5. Streamlines at Darcy number Da=10^{-3} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$sinusoidal wall case.



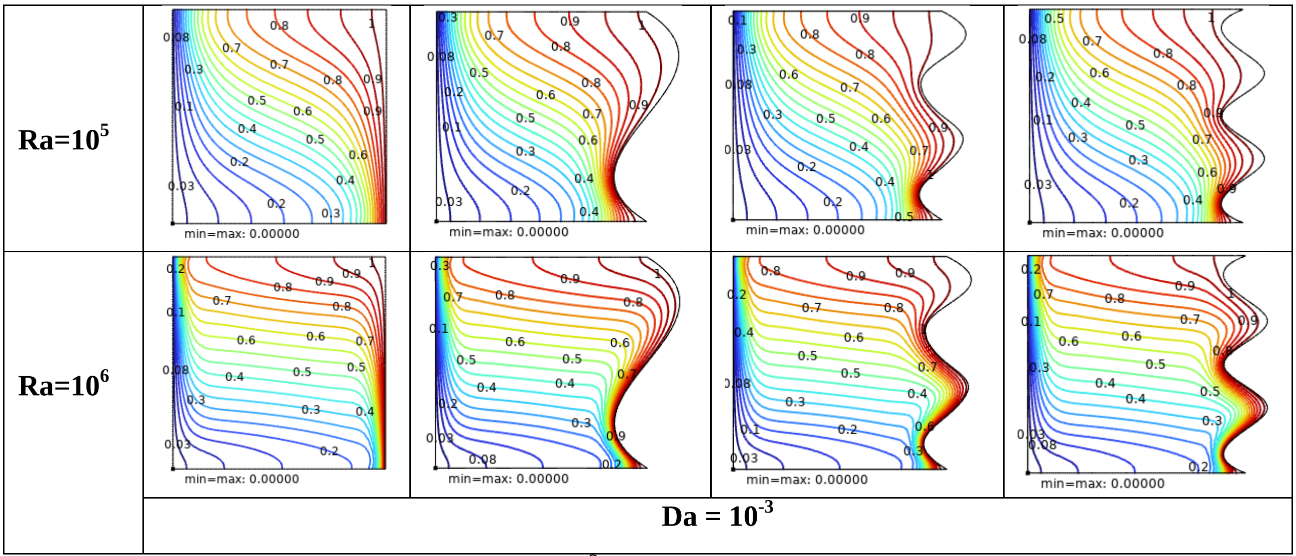


Fig 6. Isotherms at Darcy number Da=10^{-3} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$in the case of sinusoidal wall.

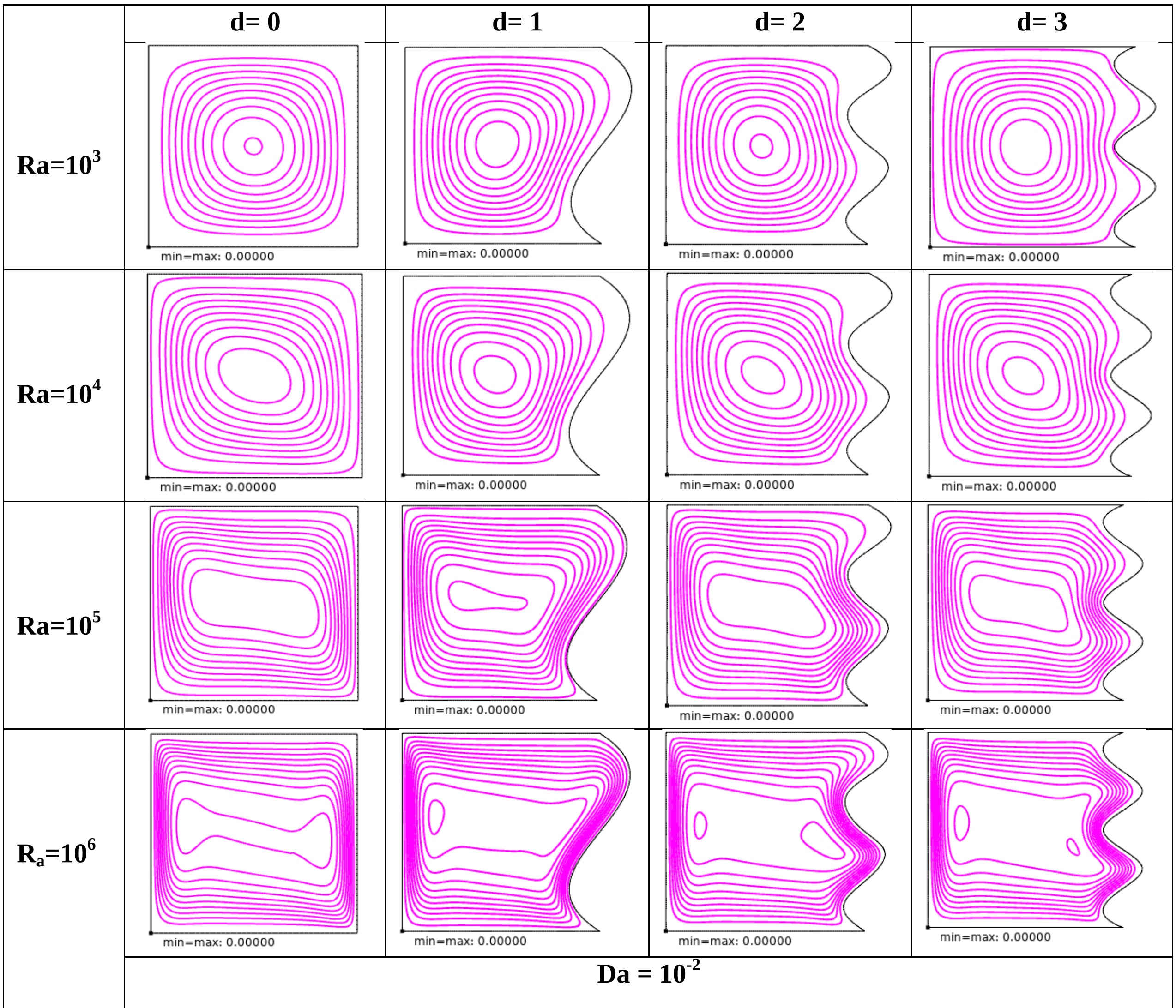


Fig7. Streamlines at Darcy number Da=10^{-2} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$ in case of sinusoidal wall.

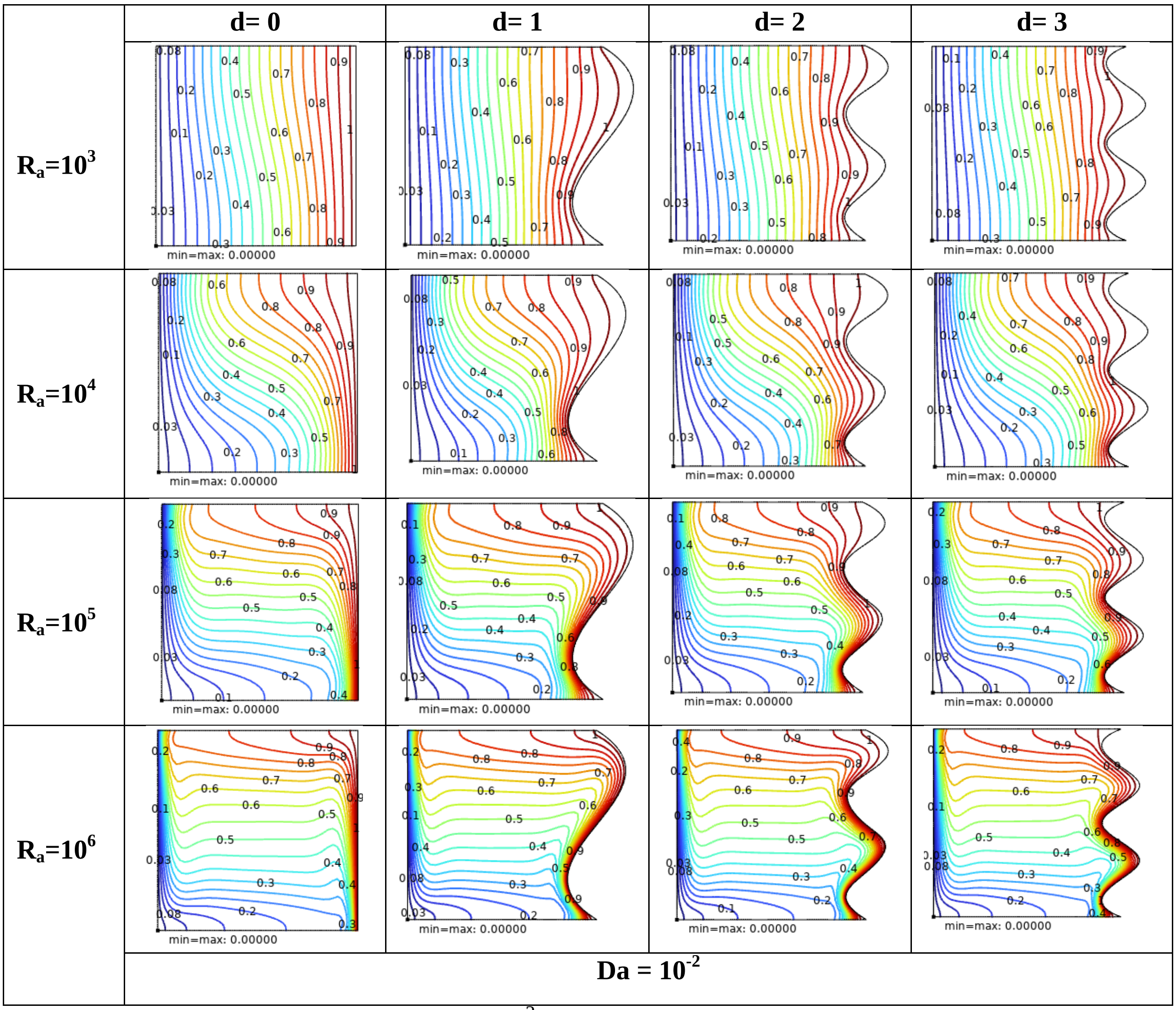
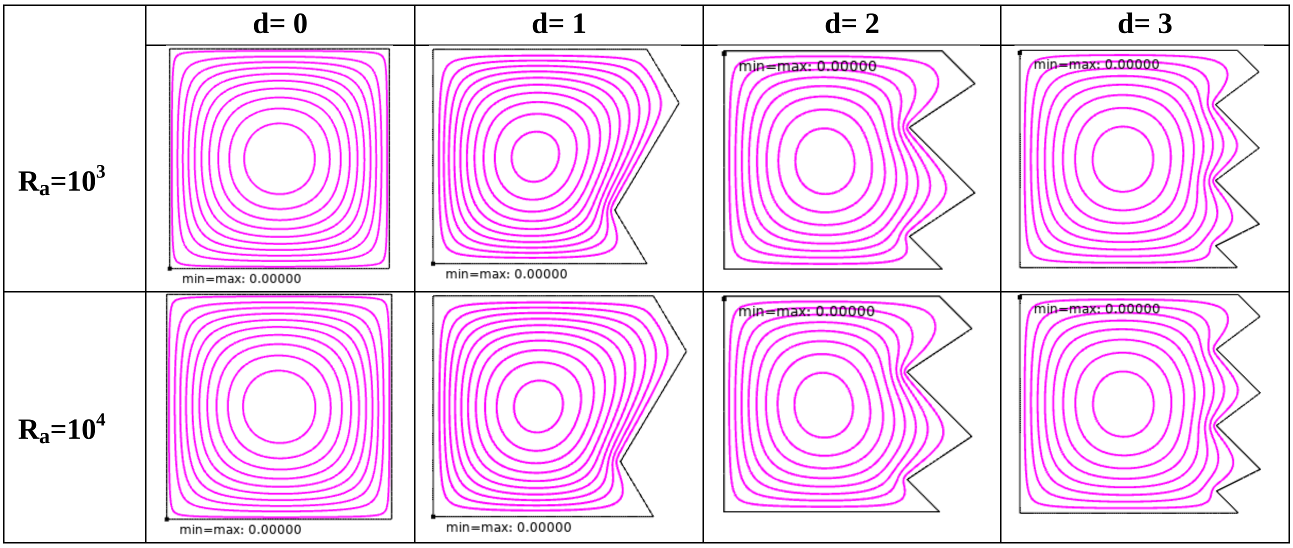


Fig 8. Isotherms at Darcy number $Da=10^{-2}$ with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$in case of sinusoidal wall.



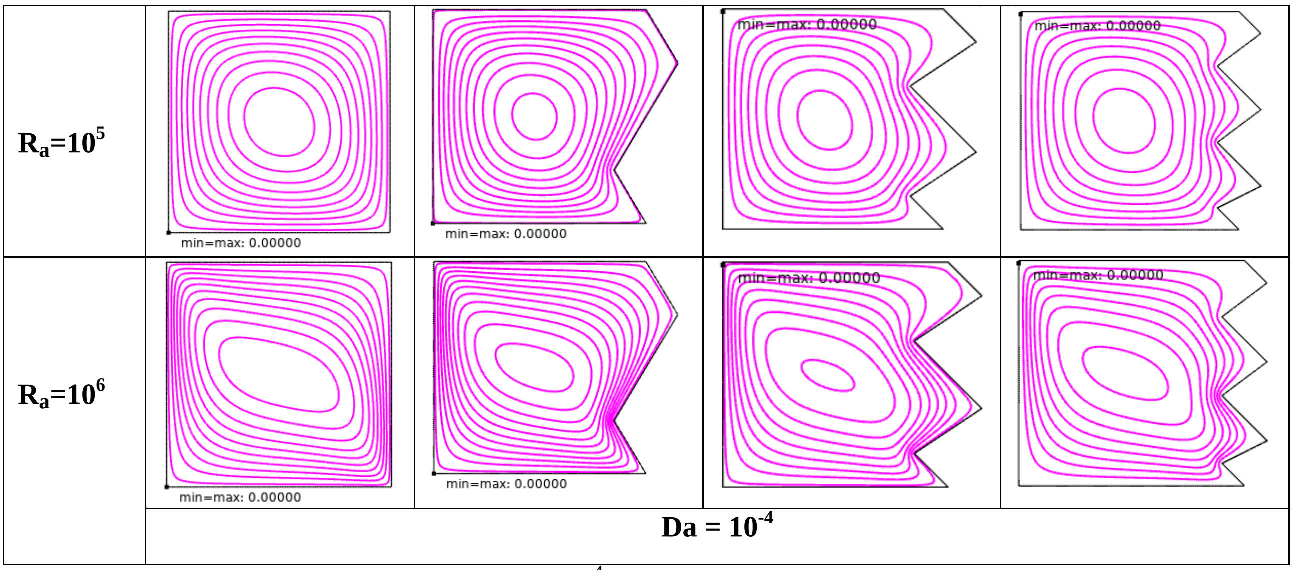


Fig9. Streamlines at Darcy number Da=10^{-4} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$in case of zig zag wall.

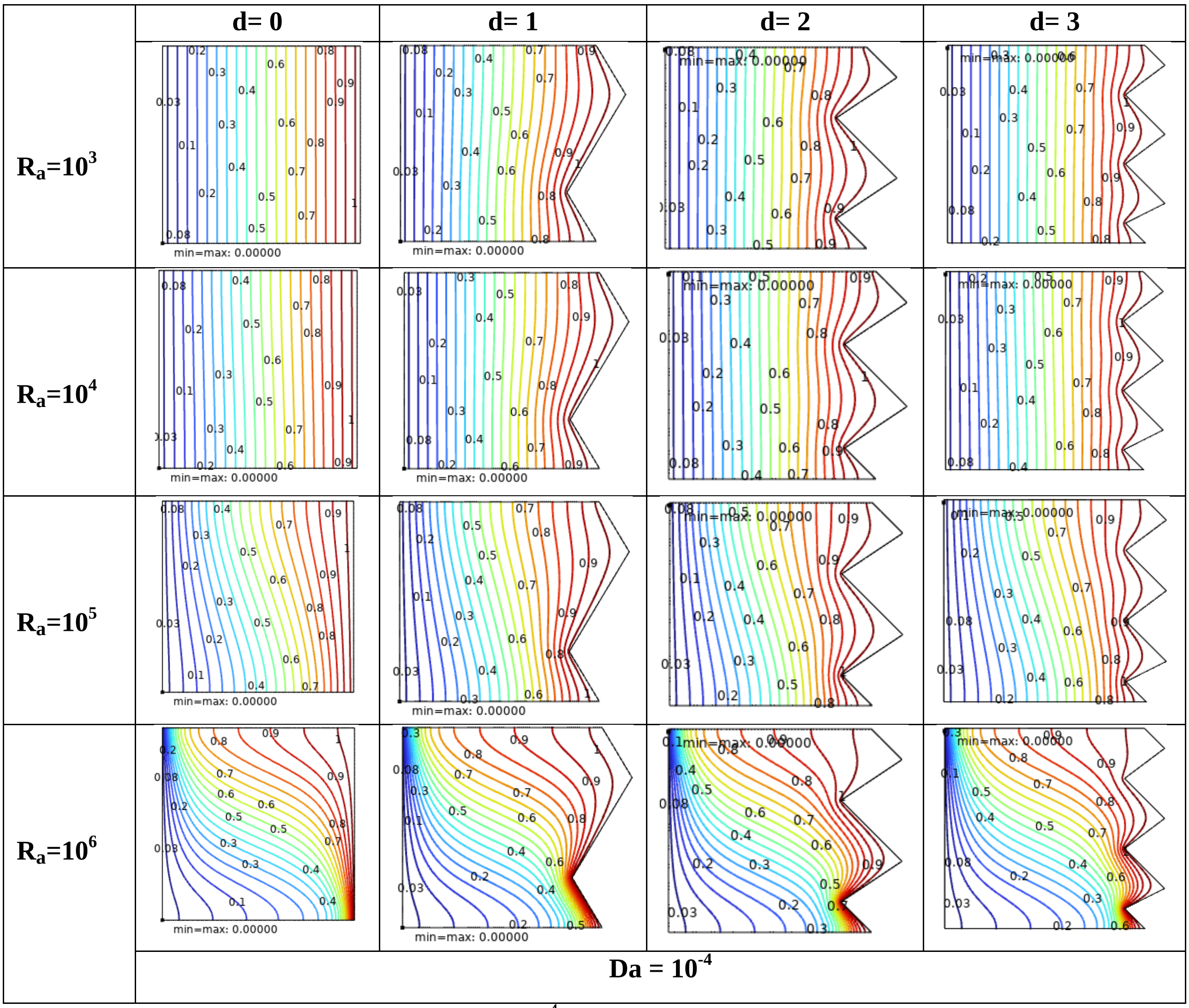


Fig 10. Isotherms at Darcy number Da=10^{-4} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$in case of zig zag wall.

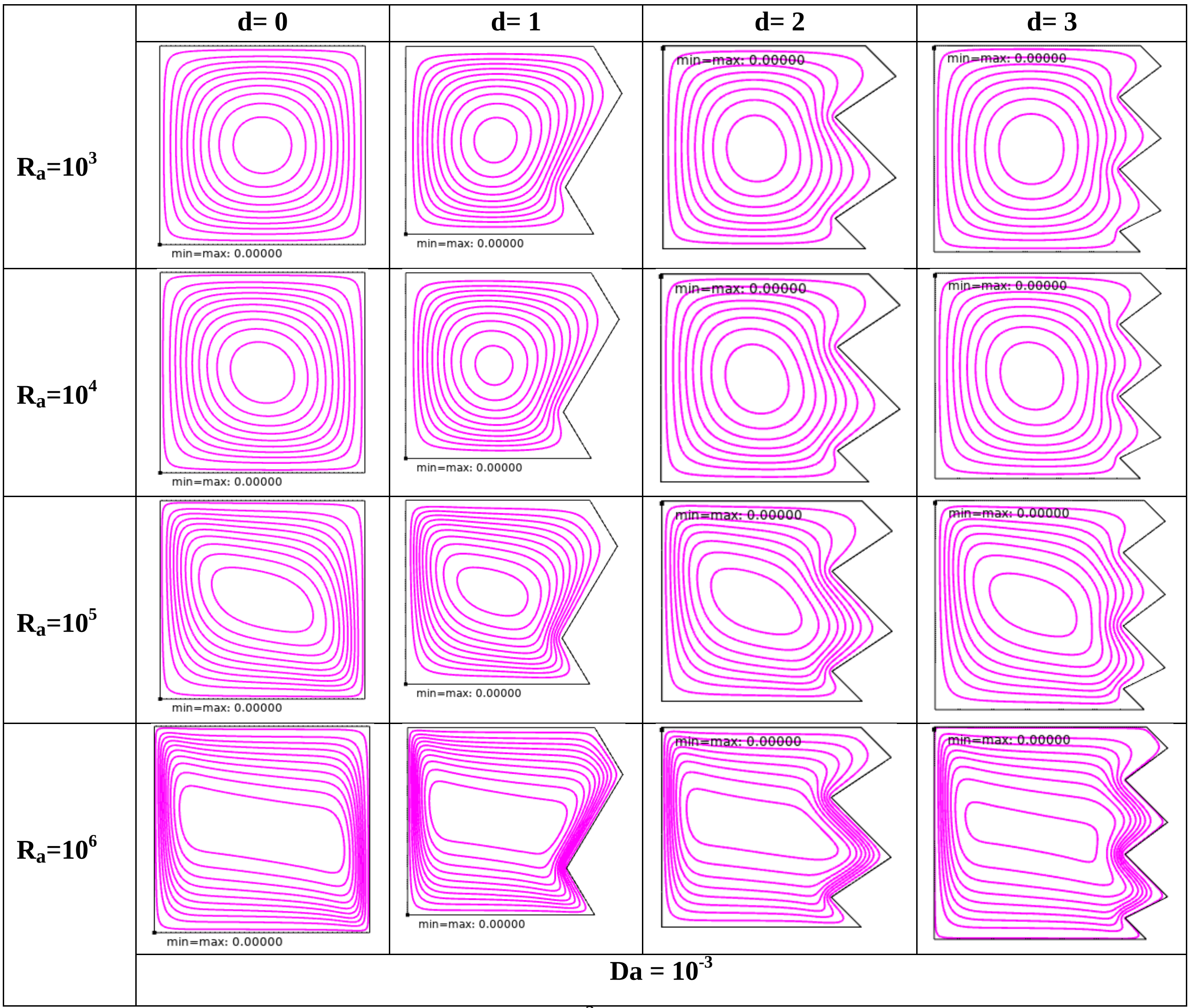
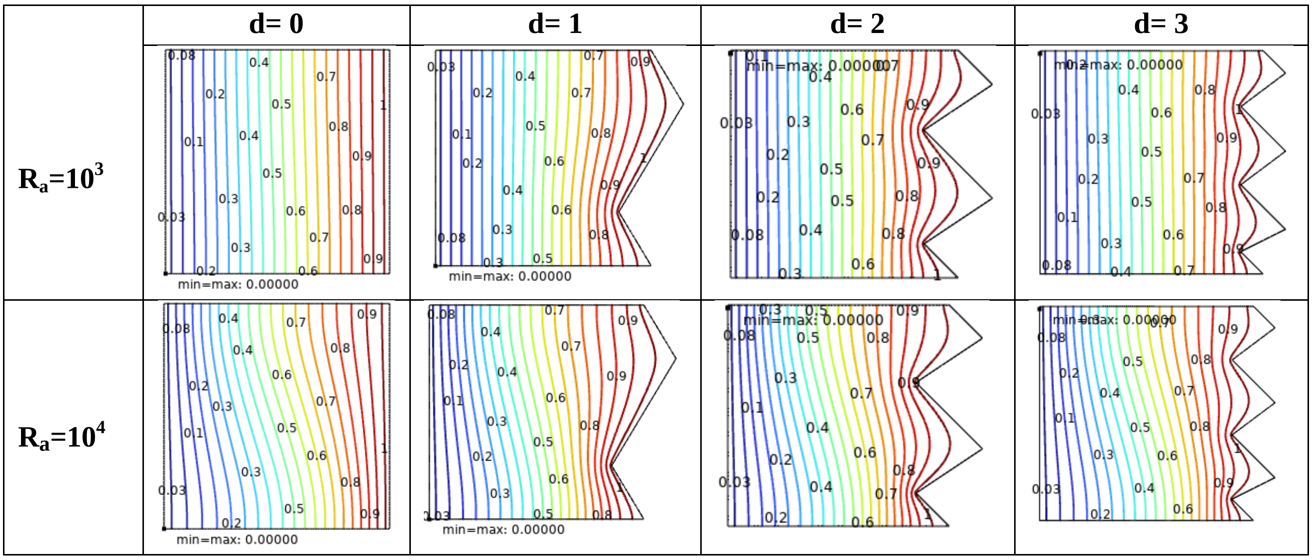


Fig 11. Streamlines at Darcy number Da=10^{-3} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \le Ra \le 10^6$in case of zig zag wall.



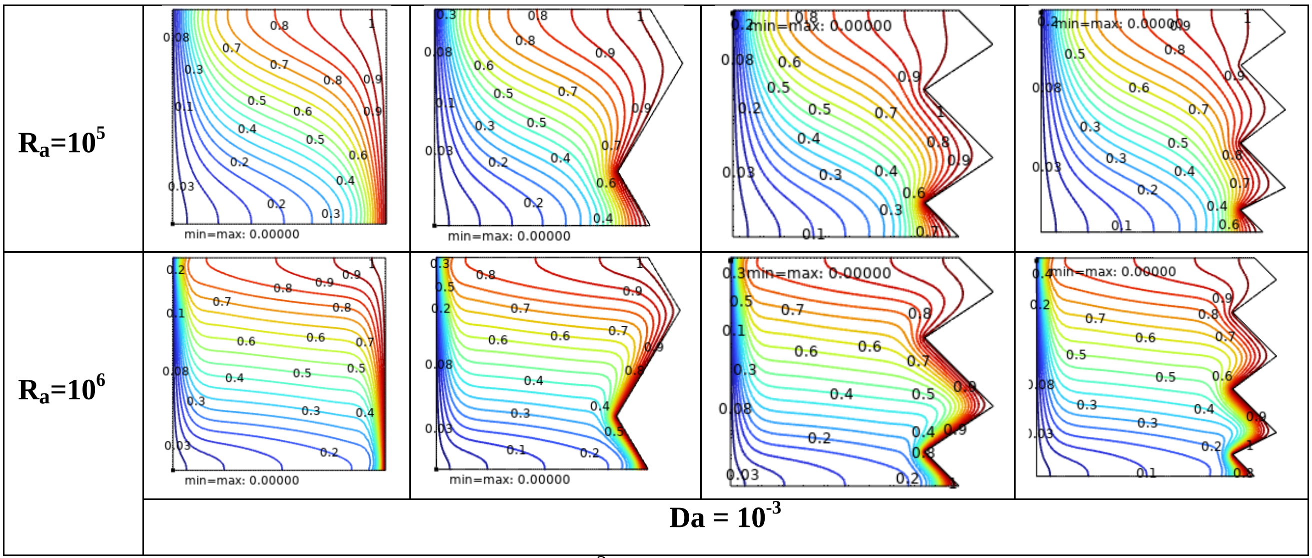


Fig 12. Isotherms at Darcy number Da=10^{-3} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq$Ra$\leq 10^6$in case of zig zag wall.

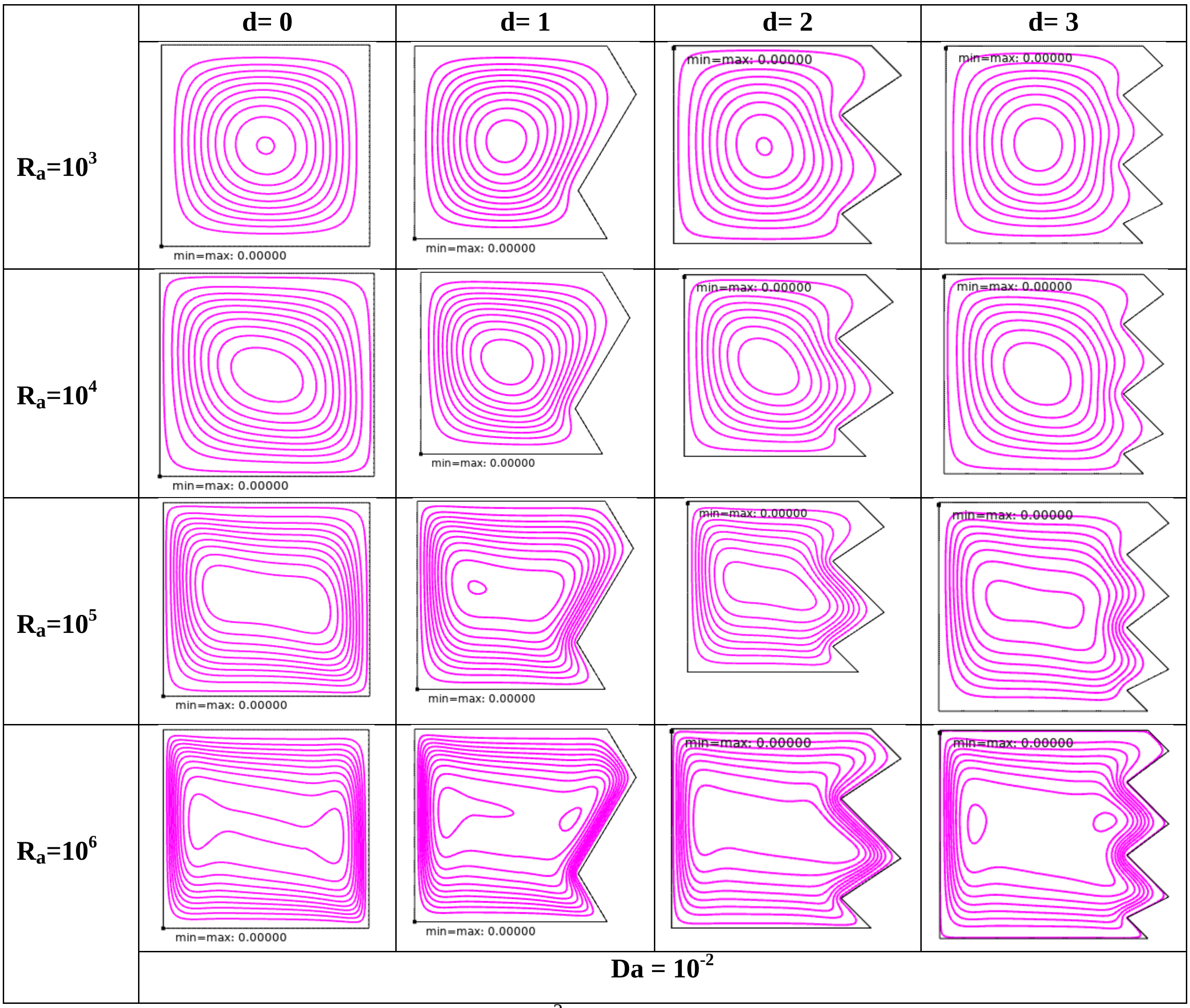


Fig13. Streamlines at Darcy number Da=10^{-2} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq$Ra$\leq 10^6$in case of zig zag wall.

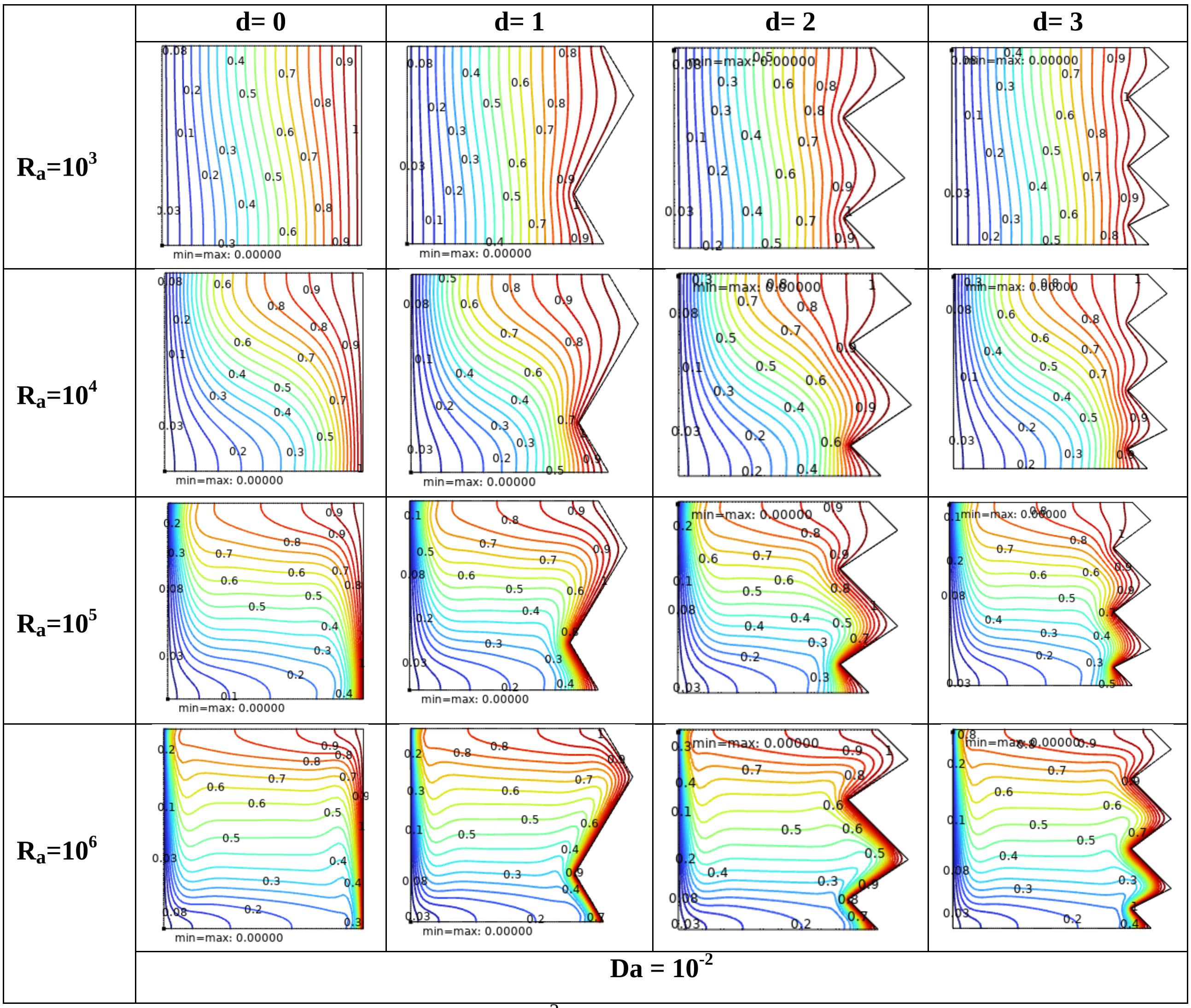
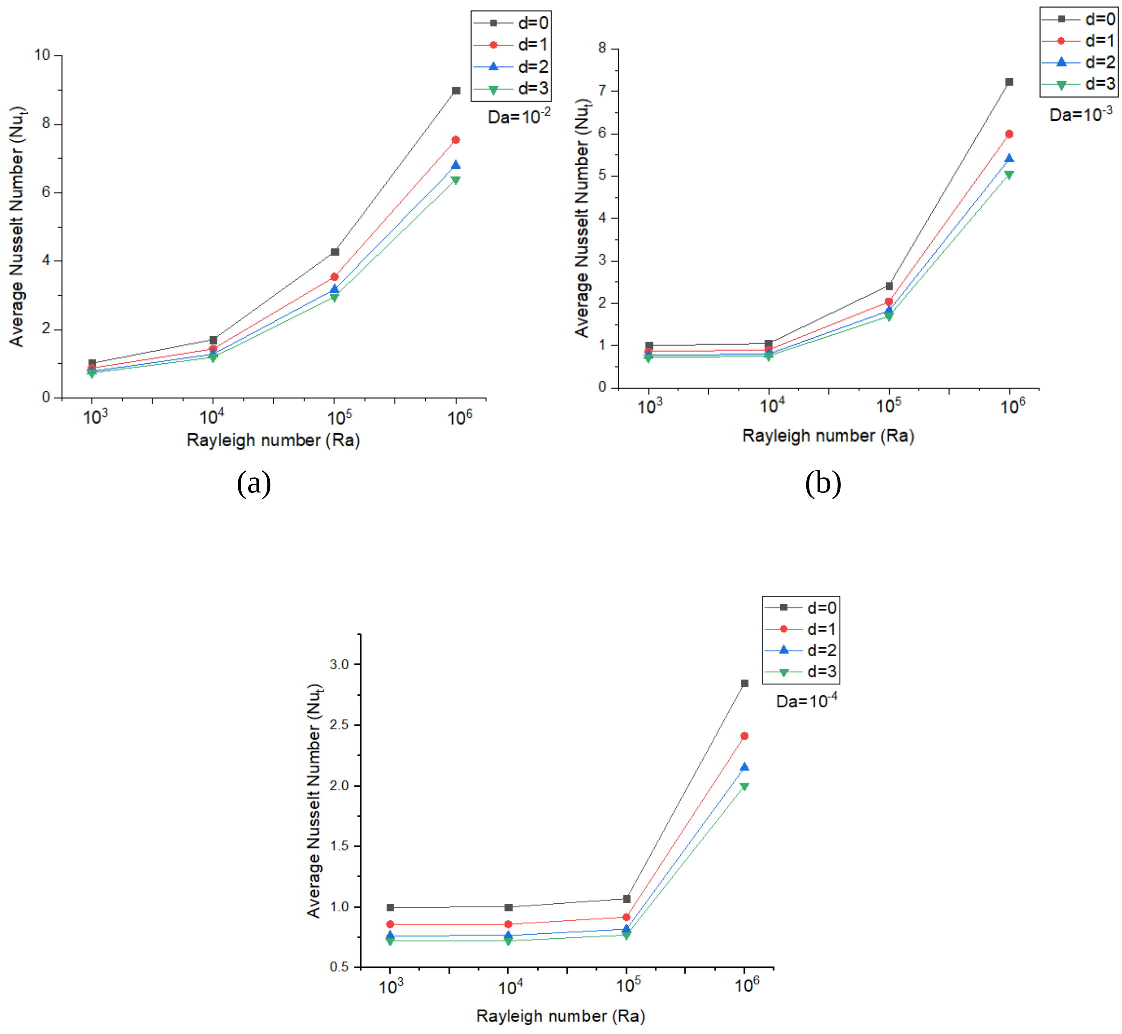


Fig 14. Isotherms at Darcy number Da=10^{-2} with different undulationsfrom (d=0 to d=3) and Rayleigh number $10^3 \leq Ra \leq 10^6$in the case of zig zag wall

4.2. Nusselt number:

Fig15 illustrates combined outcome of Ra, Da, and d on heat transmission for each sinusoidal side wall example from Da = 10^{-2} to Da = 10^{-4}. At any given Ra and Da, the rate of Nu_t is smaller for the sinusoidal side wall case with undulation d = 1 to d = 3 than for the case with undulation d = 0.And as the number of undulations increases, the Nu_t value decreases further. This is because the sinusoidal side wall introduces additional complexity and irregularity to the flow, which could lead to increased turbulence and mixing. This may cause more heat transfer across the boundary layer and into the bulk fluid, resulting in lower Nu_t. Another possible reason is that the sinusoidal side wall may cause the flow to become more asymmetrical or oscillatory, which could interfere with the natural convection patterns and reduce heat transfer.

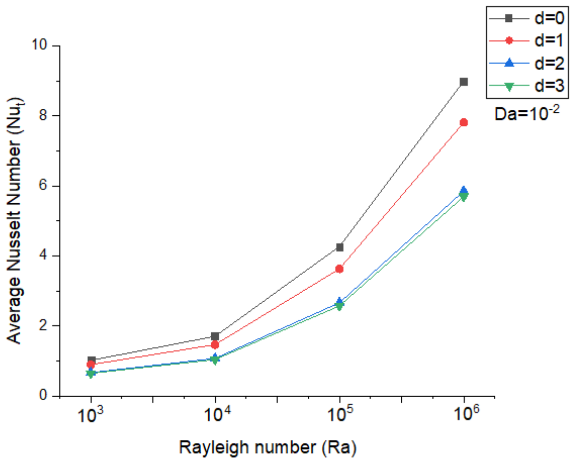


(a) (b)

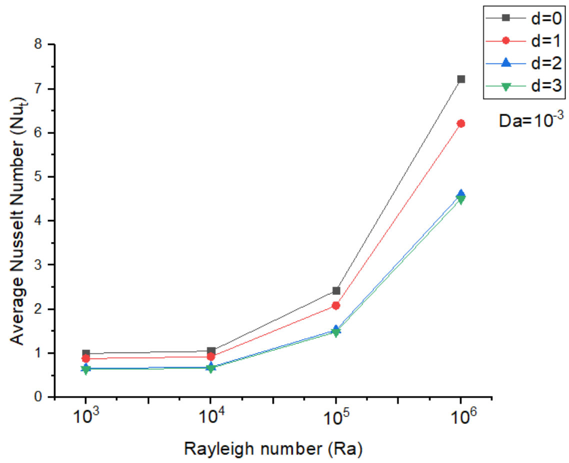
(c)

Fig 15. Average Nusselt number variations w.r.t different undulations from (d=0 to d=3) for sinusoidal side wall and Rayleigh number Ra=10^3 to 10^6 at (a)Darcy number Da=10^{-2} (b) Darcy number Da=10^{-3} (c) Darcy number Da=10^{-4}

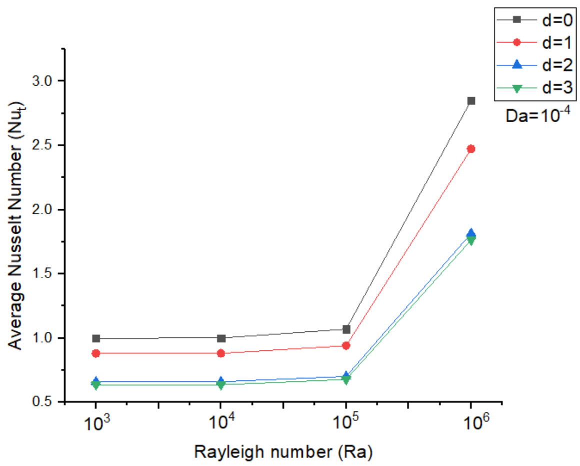
Fig. 16 shows the variation of Nu_t with respect to Ra for different undulation (d =0, 1, 2, 3) and different Darcy number ($10^{-4} \leq$ Da $\leq 10^{-2}$), for zig zag side wall case. In this for each Da, the Nu_t value for zig zag side wall when d = 0 increases with Ra, while for d = 1, 2, 3 undulations, the Nu_t value is lower than that of d = 0 case. This is because the undulation causes increase in flow resistance in flow path, this increased resistance may result in reduced fluid flow and heat transfer rate, which leads to lower value of Nu_t.



(a)



(b)



(c)

Fig 16. Average Nusselt number variations w.r.t different undulations from (d=0 to d=3) for zig zag side wall and Rayleigh number $10^3 \leq Ra \leq 10^6$at (a)Darcy number $Da=10^{-2}$ (b) Darcy number $Da=10^{-3}$ (c) Darcy number $Da=10^{-4}$

The Da, which represents the ratio of viscous forces to inertial forces have a considerable impact on flow and heat transmission properties.At higher Da, the flow is more dominated by viscous forces and less affected by the presence of the sinusoidal or zig zag side wall. And at lower Da, the flow is more inertial and more sensitive to the irregularities introduced by the sinusoidal or zig zag side wall.

5. Conclusion

The current numerical work looks at natural convection heat transfer in a square porous enclosure with non-uniform side wall with different undulation that operate as a hot wallT_h. The outcomes are displayed through streamline isotherm plots, and average Nusselt number for $10^3 \leq Ra \leq 10^6$, $10^{-4} \leq Da \leq 10^{-2}$ and for different undulation $(0 \leq d \leq 3)$ for sinusoidal and zig zag wall case.The following are the key findings of the current study:

- At Da = 10^{-4}, the conduction mode of heat transmission dominates in the enclosure. Because conduction dominates over convection, temperature fields and heat stream for all undulations and Rayleigh numbers are almost symmetrical, at Rayleigh number 10^6 minor convection currents are observed.
- The effect of convective heat movement is most visible when Da = 10^{-3}. The flow and temperature fields break symmetry when Ra $\geq 10^5$.
- At Da = 10^{-2} Nu_t increases more vigorously for higher Rayleigh number.
- A faster rate of heat transmission has been observed on sinusoidal wall case at d $\geq$ 2 compare to zig zag wall case, whereas at d$\leq$ 1 heat transmission rate is more in zig zag wall case.
- The heat transmission rate is higher at flat side wall case compare to non-uniform side wall,greater Nusselt number (Nu_t) value is observed at d=0 undulations from Da=10^{-4} to Da=10^{-2} in all the cases.
- With the increase in Rayleigh number ($10^3 \leq Ra \leq 10^6$) and Darcy number ($10^{-4} \leq Da \leq 10^{-2}$) there is increase in heat transmission rate in the porous enclosure.
- That is because as the Da is increased the porous medium become more permeable which allows the fluid to flow more easily through it and as the Ra increases the buoyancy force become more stronger than viscous forces this leads to the formation of larger and more vigorous convection cell this help to transport heat more efficiently.

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