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Analyzing Mixed Convection Recirculation in a Square Vented Enclosure with an Inlet-Outlet Flows using COMSOL

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Abstract

This study explores mixed convection flow vertically in a square vented enclosure with heating or cooling one of the vertical walls and the other three walls were insulated by using a COMSOL. This study is performed on buoyancy supported and buoyancy resistant flows. Nondimensional governing equations were employed to analyse flow and thermal behaviours for various values of Richardson number (Ri). Streamlines and isotherms reveal significant impacts from both supporting and resisting buoyancies. Buoyancy supported flow, utilizing buoyant forces, dictates flow direction and intensity, leading to distinct streamlines and temperature contours. In contrast, buoyancy-resistant flow, influenced by opposing wall forces, generates varied flow patterns and temperature distributions.

1. Introduction

Mixed convection is a phenomenon that occurs when both forced convection and natural convection have important effects on a system's heat transfer and fluid movement [1]. There are several technological and commercial applications of forced convection in nature, such as solar receivers exposed to wind currents, electronic devices cooled by fans, and ocean and atmospheric movements.

Early studies of mixed convection were conducted in a heated hemisphere a Bingham plastic. There are four nondimensional parameters, which are Reynolds number, Prandtl number, Richardson number and Bingham number, used for describing the momentum and heat transfer characteristics [2]. Next, the dimensionless governing equations such as continuity, momentum and energy transport were implemented in COMSOL The study examined the properties of mixed convective and fluid flow in an air-filled lid-driven enclosure with its walls heated to different temperatures. The Grashof and Reynolds values for each cavity wall have an impact on the average Nusselt number. Streamlines are used to assess the flow characteristics, and isotherm contours are used to look at the related heat transfer characteristics and define each of these parameters [3].

Besides that, numerous studies have been conducted that collectively contribute to how strategic heat source placement, buoyancy forces, fluid flow variations, and specific positions within vented enclosures can either support or impede mixed convection recirculation. They analysed the impact of heat source positions on various parameters. It also involves designing more effective heat exchangers or cooling systems by understanding and manipulating mixed convection dynamics for improved thermal management. [4-7].

The problem of mixed convection flows within a vertically in a square vented enclosure is examined in this work. The investigation specifically focuses on scenarios where one of the vertical walls is subjected to heating or cooling while the other three walls are insulated. Three parameters are used, which are the Prandtl, Reynolds, and Richardson numbers. COMSOL Multiphysics is employed to analyse the influence of these parameters on streamlines and isotherms. This study is an extension of the research conducted by Dhahad [8]. Previous research used the high-order spectral element technique to identifies streamlines and isotherms in fluid dynamics. Meanwhile, we identified the impacts on streamlines and isotherms by using COMSOL Multiphysics with difference values of parameters, and boundary conditions.

Nomenclature	
C_p	Specific heat capacity
d	Enclosure inlet slot or outlet vent width
Gr	Grashof number
H	Enclosure height
k	Thermal conductivity
p	Pressure
P	Dimensionless pressure
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
T	Temperature
t	Time
u	Horizontal velocity
U	Dimensionless vertical velocity
v	Vertical velocity
V	Dimensionless vertical velocity
x, y	Cartesian coordinates
X, Y	Dimensionless cartesian coordinates
Greek symbols	
α	Thermal diffusivity
β	Volumetric expansion coefficient
θ	Dimensionless temperature
ρ	Density
μ	Dynamic viscosity
ν	Kinematic viscosity
τ	Dimensionless time
Subscripts	
o	Inlet condition
w	Wall

2. Methodology

This analysis is done with the aid of COMSOL Software. COMSOL is used for computing streamlines and isotherms under different scenarios, such as heating or cooling on the one of the left vertical walls and three walls are insulated. It employs models for laminar flow, heat transfer, and Poisson's equation in fluids to effectively solve these problems.

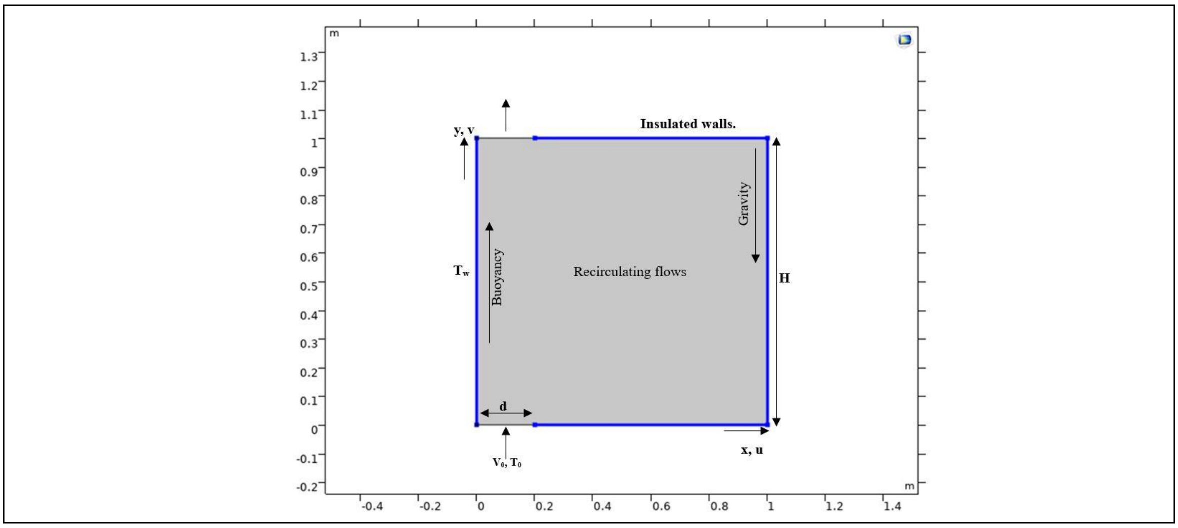

Figure 1: *The used coordinate system and geometric parameters [8]*

Figure 1 shows the 2D model of the square enclosure. The left wall is heated or cooled, and the other three walls are insulated. It displays the study region, significant geometrical properties, and selected coordinate system. It comprises a square enclosure with lengthwise sides. In COMSOL, the enclosure inlet slot and outlet vent width, d are set to 0.2m. Although it is considered that the horizontal and right vertical walls are insulated, the buoyancy effects are caused by temperature differences between the inflow fluid and the enclosure's left vertical wall as compared to that wall and the fluid.

However, depending on whether the wall temperature, T_w is higher or lower than inlet temperature, T_0 of the entering fluid flow, the buoyancy effect will either be aiding or resisting. The causing resisting mixed convection when the cooling effect is greater than the heating impact.

By taking the above assumptions, the equation below are written in terms of the velocity u and v , pressure, p and temperature, T as:

The conservation of mass equation:

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

Momentum equation:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial \rho}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial \rho}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g\beta(T-T_0) \tag{3}$$

Energy equation:

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

Then, the dimensionless equation is formed by substituting the following scaling parameters into a dimensional equation:

$$U=\frac{u}{v_0},\quad V=\frac{v}{v_0},\quad X=\frac{x}{H},\quad Y=\frac{y}{H},\quad P=\frac{\rho}{\rho v_0{}^2},\quad Gr=\frac{g.\beta.H^3(T_w-T_0)}{v^2}$$

$$\mathrm{Re}=\frac{v_0 H}{v},\quad \theta=\frac{T-T_0}{T_w-T_0},\quad Ri=\frac{Gr}{\mathrm{Re}^2},\quad \mathrm{Pr}=\frac{v}{a},\quad \tau=\frac{v_0 t}{H}$$

Due to the research of a mixed convection flow in a vertically square vented enclosure with heating and cooling one of the vertical walls and the other three walls are insulated [8] was the problem used in this study, so all of the equations subjected to the boundary conditions will be used and studied in this thesis. The nondimensional system equations are as below:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{5}$$

$$\frac{\partial U}{\partial X}+\left(U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}\right)=-\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{6}$$

$$\frac{\partial V}{\partial \tau}+\left(U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=-\frac{\partial P}{\partial Y}+\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ri\theta \tag{7}$$

$$\frac{\partial \theta}{\partial \tau}+\left(U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}\right)=\frac{1}{\mathrm{Re.Pr}}+\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{8}$$

The nondimensional initial and boundary conditions of the problems are as below:

The velocity $U_0=0$, $V_0=1$ and temperature are uniform at the inlet slot, when the condition of left vertical wall is heated, $\theta_0=0$ and left vertical wall is cooled, $\theta_0=1$,respectively.

On the left vertical wall of enclosure, a no slip boundary condition indicating that the fluid stick to wall, $U_w=V_w=0$ and a uniform temperature when the left vertical wall is heated, $\theta_w=1$ and left vertical wall is cooled, $\theta_w=0$.

The no slip requirement is also enforced on the enclosure's right vertical and horizontal walls, and the gradient of temperature normal to the walls is set to zero, which indicates that these walls are insulated, $U=V=0$. Other previous studies were done in flow application in worldwide according to various fields of studies [9, 10].

3. Results and Discussion

This section discusses the effect of heating and cooling on the left vertical wall with inlet-outlet flows in a square vented enclosure. Streamlines show the direction and flow patterns of fluid motion, representing the path taken by a fluid particle. Furthermore, isotherms show the temperature distribution in the simulated system and contours.

There are three parameters used to compute the streamline and isotherms which are the Reynolds number, Prandtl number and Richardson number. A Reynolds number of 50 is selected due to the low flow velocity, potentially leading to laminar flow. The Prandtl number of 0.707 accurately represents air's thermal properties. Lastly, various Richardson numbers of 0, 1, 5, and 10 are chosen to describe the ratio of buoyancy to shear effect in fluid and to exploring different buoyancy effects.

3.1 The left vertical wall heated

3.1.1 Streamlines

Figure 2 shows the pattern of a streamline when the left vertical wall heated with the fixed values of Reynolds number 50, Prandtl number 0.707, and Richardson numbers 0, 1, 5, and 10, which were solved by COMSOL. For Ri = 0, the buoyancy effects are small. The forced flow resulting from the inlet and outlet will impact the streamlines. It will resemble conventional forced convection, appearing more uniform and aligned with the direction of the forced flow.

However, for Ri = 1, there is a transition between forced and natural convection. The buoyancy forces start to become significant compared to the forced flow but are not dominant. The streamlines show both buoyancy-induced and forced effects. The apparent alterations in flow patterns, which deviate slightly from forced flow behaviors due to buoyancy effects and become more significant.

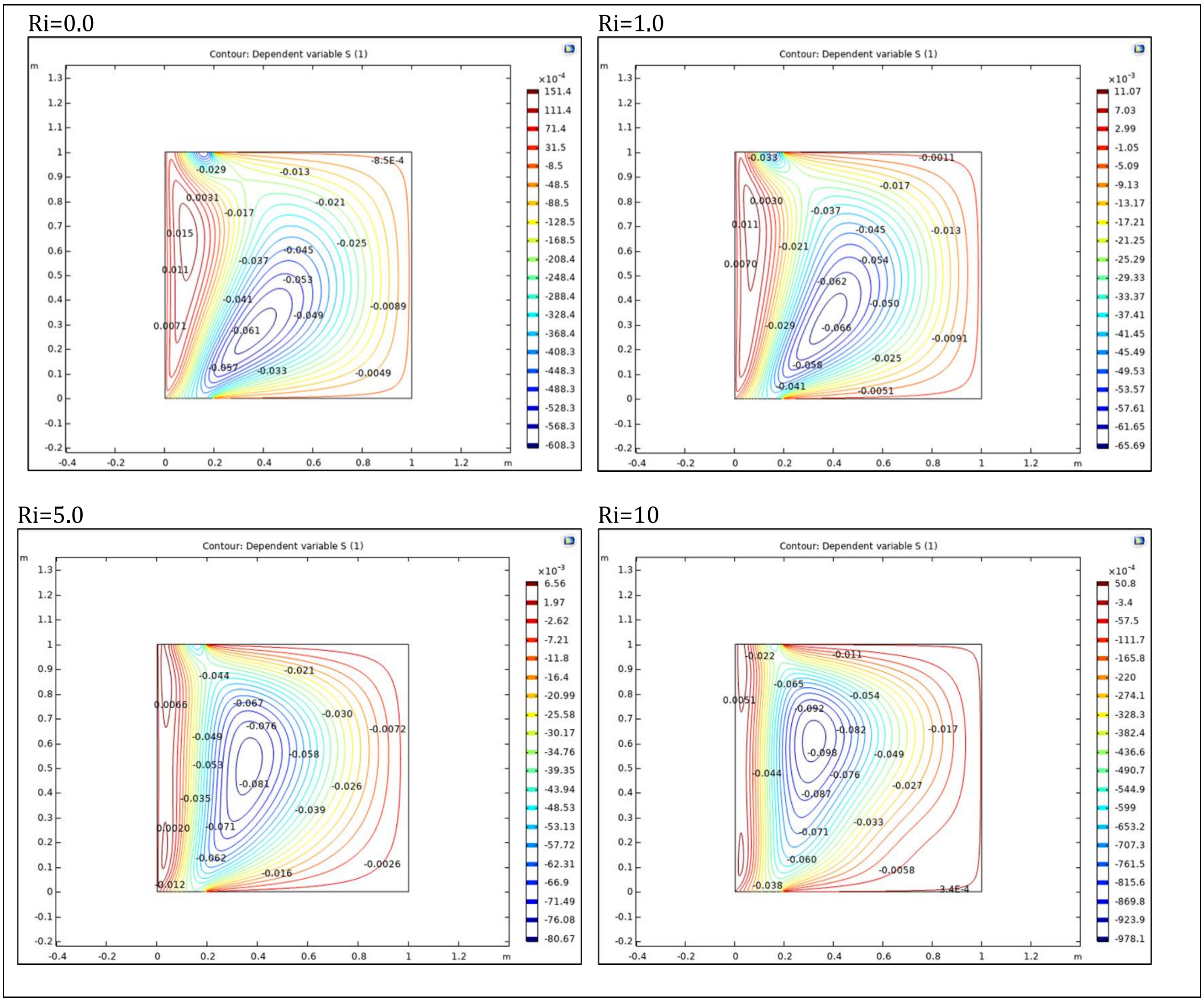

Figure 2: *Patterns streamlines for Re = 50, Pr=0.707 and at various Ri.*

Moreover, at Ri = 5 and Ri = 10, there are more prominent buoyancy effects. The effect of natural convection increases with the Richardson number, which indicates stronger buoyant forces relative to the driven flow. There is a notable divergence between the streamlines and the situation of pure forced convection. The interaction of forced and buoyancy-driven flow results in increasingly complicated flow patterns that show vortices, recirculation zones, and convective cells.

3.1.2 Isotherms

Figure 3 shows the pattern of a isotherms when the left vertical wall heated with the fixed values of Reynolds number 50, Prandtl number 0.707, and Richardson numbers 0, 1, 5, and 10, which were solved by COMSOL. For Ri=0, it was occurred purely by forced convection. Since the heated left vertical wall and the incoming fluid have different temperatures, isotherms primarily followed the route of forced convection. Temperature gradients primarily aligned with the direction of the forced flow and exhibit a relatively uniform temperature distribution across the enclosure. There were fewer buoyancy-driven effects and greater efficiency in the isotherms.

However, for Ri = 1, there was a transition between forced and natural convection. The forced convection and buoyancy effects were similar, but the isotherms exhibited differences. Temperature gradients have changed locally, especially close to the heated wall, indicating that buoyancy-driven factors have started to affect the flow. The combination of forced and natural convection caused the isotherm pattern to be seen.

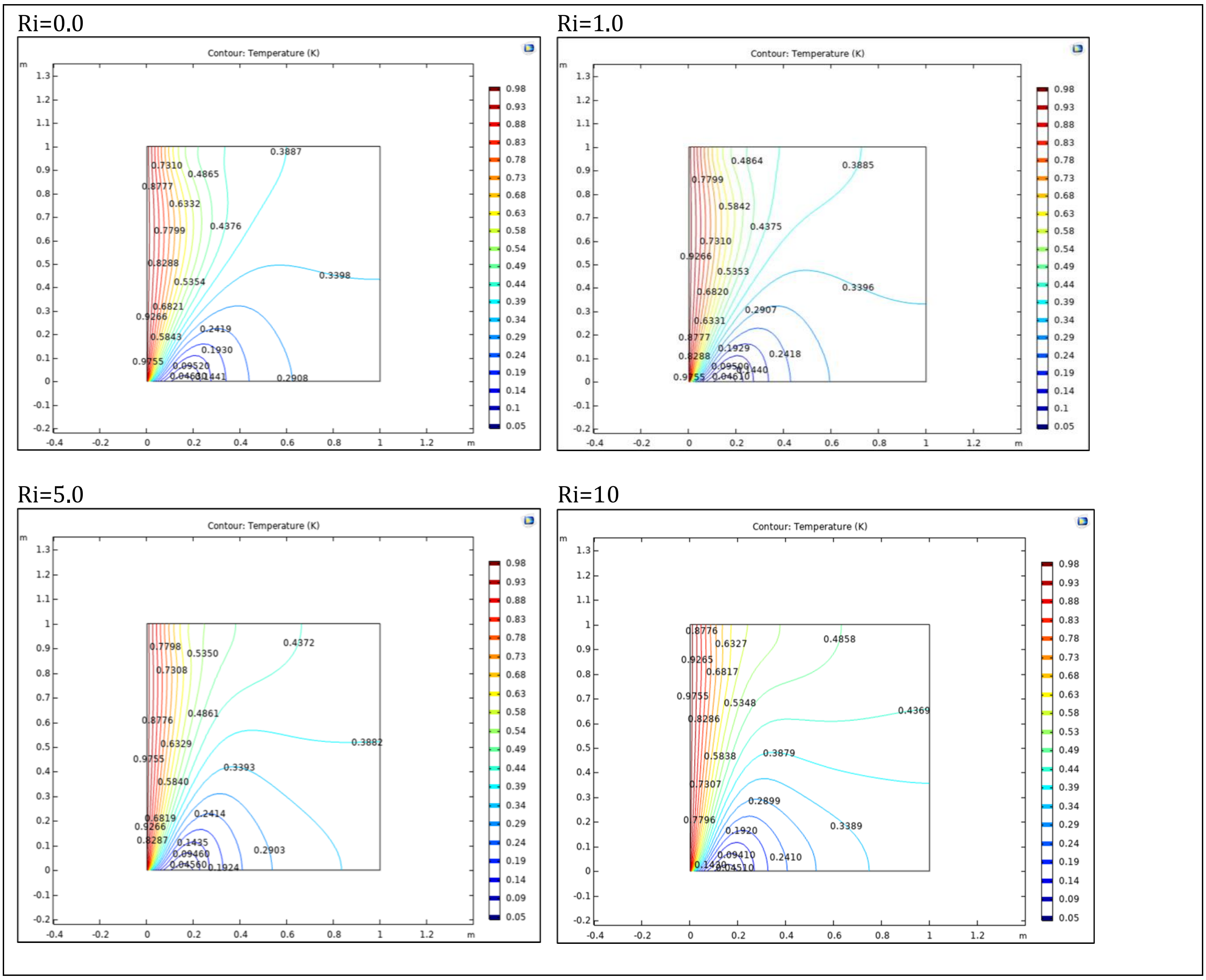

Figure 3: *Patterns isotherms for Re = 50, Pr=0.707 and at various Ri.*

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Furthermore, for Ri = 5 and Ri = 10, the buoyancy effects became particularly prominent. The effect of buoyancy-induced flow rises with increasing Richardson numbers. A more apparent deviation from the forced convection pattern can be seen in the isotherms. The combination of forced and buoyancy-driven convection processes created regions with greater temperature gradients, recirculation zones, and convective cells. The complex patterns of the isotherms near the heated wall indicated significant buoyancy forces causing intense mixing and heat transfer.

3.2 The left vertical wall cooled

3.2.1 Streamlines

Figure 4 shows the pattern of a streamlines when the left vertical wall cooled with the fixed values of Reynolds number 50, Prandtl number 0.707, and Richardson numbers 0, 1, 5, and 10, which were solved by COMSOL. For Ri = 0, there was an indication of negligible buoyancy effects compared to forced convection. The streamlines followed the path determined by the forced flow from the inlet and exit vents. Inside the enclosure, the streamlines were largely straight and uniform because of the pressure difference between the inlet and outlet. Streamlines exhibited less deviation from the directed flow path because buoyancy-induced effects were negligible.

However, for Ri = 1, the change from forced to natural convection occurred. As the buoyancy and forced convection effects start to become comparable, there might be slight deviations in the streamlines. The presence of cooling on one vertical wall caused localised variations in the flow path near that wall, leading to minor

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perturbations in the streamlines. However, these deviations did not significantly alter the overall flow patterns compared to the purely forced convection case.

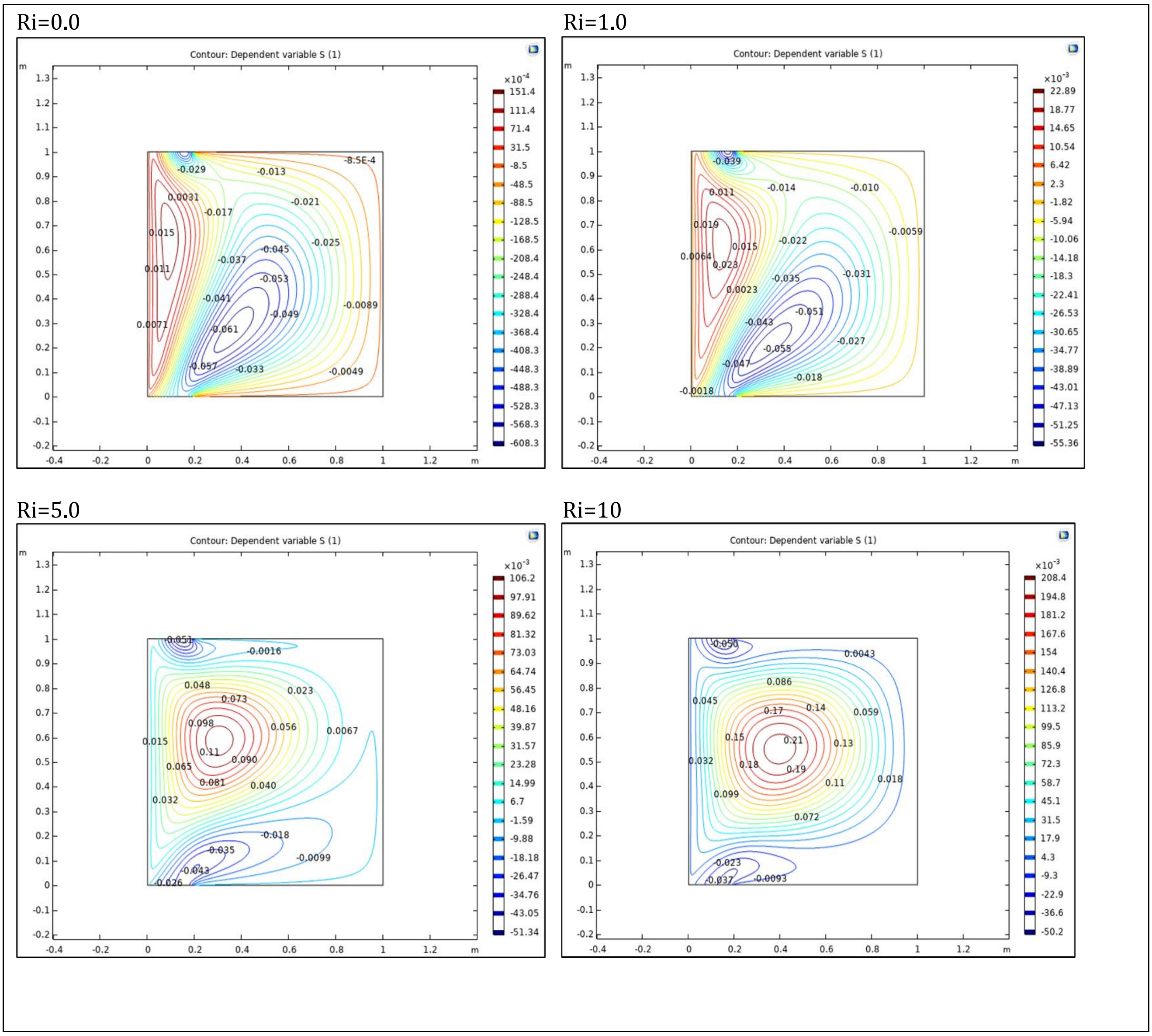

Figure 4: *Patterns streamlines for Re = 50, Pr=0.707 and at various Ri.*

Furthermore, for Ri = 5 and Ri = 10, as the Richardson number increased, the streamlines showed increasingly pronounced departures from simply forced convection. The complex flow patterns resulted from stronger buoyant forces brought on by the temperature difference between the cooled wall and the incoming fluid. As buoyancy effects increased, streamlines exhibited curvatures, vortices, and recirculation zones, particularly in areas affected by the cooling vertical wall.

3.2.2 Isotherms

Figure 5 shows the pattern of isotherms when the left vertical wall cooled with the fixed values of Reynolds number 50, Prandtl number 0.707, and Richardson numbers 0, 1, 5, and 10, which were solved by COMSOL. Concerning Ri = 0, purely forced convection occurred. The isotherms followed the temperature gradient created by the vertical wall's cooling, showing minimal buoyancy effects. A more even temperature distribution throughout the enclosure is indicated by isotherms that are probably parallel to the cooling wall, which provided a noticeable temperature gradient. With less impact on the flow, the insulation on the other walls helped to maintain a constant temperature.

However, at Ri = 1, there was a transition between forced and natural convection. The cooling of the vertical wall starts to induce minor perturbations in the isotherms, causing deviations from the purely forced convection scenario. Near the cooled wall, localized variations in temperature gradients had led to irregularities in the isotherm patterns.

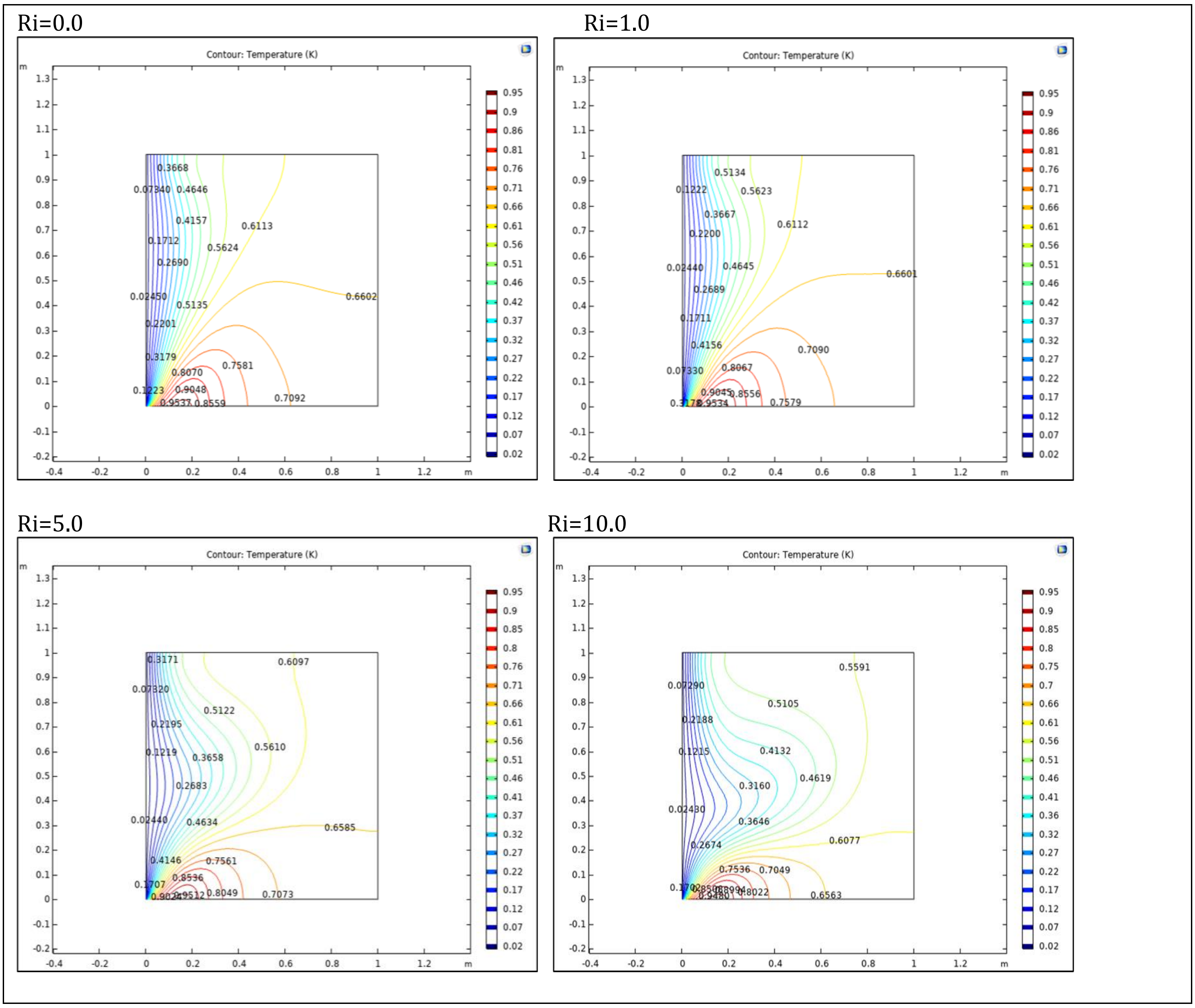

Figure 5: *Patterns streamlines for Re = 50, Pr=0.707 and at various Ri.*

Moreover, for Ri = 5 and Ri = 10, the isotherms diverged farther from the forced convection pattern. This is because an increase in the Richardson number indicates greater buoyancy effects. More intricate isotherm patterns resulted from stronger buoyant forces brought on by the temperature differences between the cooled wall and the incoming fluid. The isotherms showed more curvature, irregularities, and changes near the cooled wall, indicating the influence of buoyancy-induced flow on temperature distribution.

4. Conclusion

In conclusion, there are three parameters used, Reynolds number (Re) is 50, Prandtl number (Pr) is 0.707, and various Richardson number (Ri) which are 0,1,5 and 10. The problem's equations and boundary conditions were put into COMSOL to produce streamlines and isotherms. All of the values were used to produce the different results of streamlines and isotherms plots for both condition when the left vertical wall is heated or cooled with the inlet-outlet flows in a square vented enclosure.

Besides that, the condition of left vertical wall heated and the Richardson number rises, both streamlines and isotherms experience increased complexity and deviation from patterns observed in forced convection alone. Streamlines show heightened curvature and circulation, reflecting the interaction between natural and forced convection. Isotherms exhibit irregularities, increased bending, and variations in spacing, reflecting the impact of buoyancy-induced flow effects and complex thermal patterns resulting from the interplay between natural and forced convection.

Lastly, when the left vertical wall cooled and the Richardson number decreases, streamlines follow direct path due to external forces, mainly forced convection. These streamlines are less convoluted and unaffected by buoyancy, offering a uniform flow, especially without significant temperature gradients. However, isotherms in resistive flow depart from forced convection patterns, exhibiting greater complexity as a result of the interplay between buoyancy-driven and forced forces. The external force guiding the flow creates specific directions for heat transfer, causing isotherms to differ from purely forced convection patterns.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design, data collection, analysis, and interpretation of results****: Nur Amyliana Ash'ari and Muhamad Ghazali Kamardan;* ***draft manuscript preparation****: Nur Amyliana Ash'ari and Muhamad Ghazali Kamardan. All authors reviewed the results and approved the final version of the manuscript.*

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