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Natural Heat Convection in an L-Shaped Cavity with Flexible Wall: Effect of the Position of the Flexible Wall

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Abstract - This research endeavours to perform a numerical analysis of fluid-structure interaction (FSI) within an L-shaped cavity, with particular emphasis on the influence of Rayleigh number and the positioning of the flexible wall. A range of visualization methods, such as streamlines, temperature contours, and Nusselt number, were utilized to demonstrate the enhancement of heat transfer attributed to the presence of flexible walls. The findings indicate a significant correlation between the average Nusselt number and the Rayleigh number. Notably, the average Nusselt number was observed to have a significant representation in models featuring flexible walls in comparison to those with rigid walls. Furthermore, the configuration with a horizontal flexible wall exhibited superior performance relative to the vertical arrangement. The implications of these findings are substantial, as they offer valuable insights for optimizing heat transfer and developing effective thermal management systems for real-world applications. This study enhances the understanding of fluid-structure interaction in complex geometries, providing critical information for the design and advancement of thermal systems across various sectors.

***Keywords*:** Natural Convection, L Shaped Cavity, Nusselt Number, FSI

1. Introduction

Natural convection in odd-shaped cavities was extensively considered by many researchers due to its appearance in many applications such as thermal storage, solar collectors, nuclear reactors, and many other applications. Alshuraiaan [1] considered an L-shaped cavity with one flexible wall as an example to enhance the heat transfer process. Selimefendigil and Oztop [2] considered the effect of inclination angle on the mixed convection in an L-shaped cavity with a flexible wall and the presence of internal heat generation. Sourtiji and Hosseinizadeh [3] presented a numerical study on natural heat convection in an L-shaped with different aspect ratios with the presence of magnetohydrodynamic field and nanofluids. Shahrestani et al. [4] investigated the effect of using a flexible barrier vertically centred in a circular cavity on the heat transfer by natural convection inside the cavity. Ismael and Jasim [5] studied the effect of presence of a flexible fin inside a square cavity on the mixed convection inside a square cavity. The effect of the characteristics of a flexible wall placed on one side along with the aspect ratio of a cavity is investigated by Yaseen et al. [6]. This study is a continuation of a previous study presented by Alshuraiaan [1] in which only the inner vertical wall was chosen to be flexible. In this study, a numerical investigation of the flexible wall positioning on the natural convection in cavity of an L-shape is considered where the inner horizontal wall is also considered to be flexible.

2. Methodology

Natural heat convection in an L-shaped with where heat is transferred from one side to another while keeping the short ends insulated is analysed numerically by COMSOL Multiphysics. The physical domain along with boundary conditions are shown in Fig. [1]. The cavity long and short sides are equal, and the short side (W) is chosen to be 30% of the long side (H) as illustrated in Fig. 1. The study presented by Alshuraiaan [1] considered the flexible wall to be only the short vertical wall. Another scenario for the flexible wall will be considered in this study, the inner short horizontal wall and the inner vertical wall of length L.

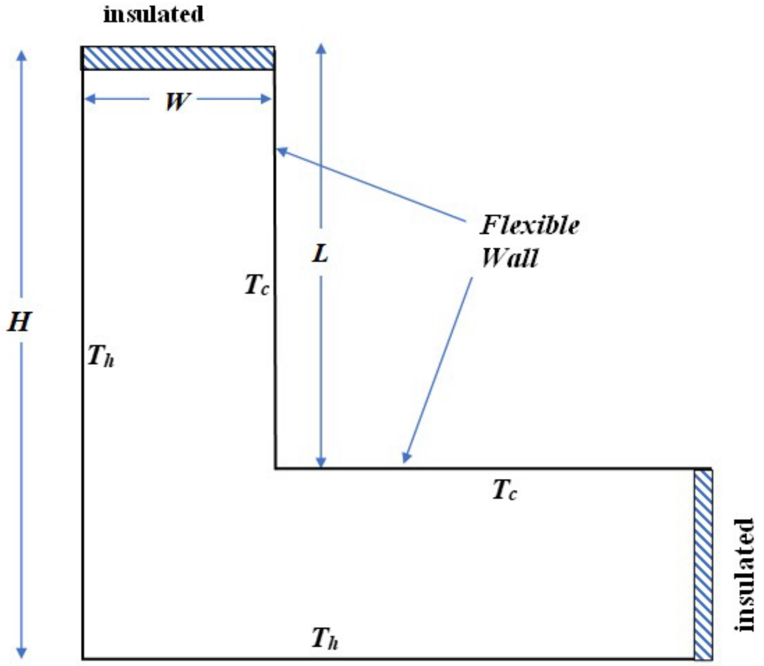

Fig. 1: Schematic diagram of the L-shaped cavity

The analysis assumes incompressible 2-D steady laminar flow with variations of fluid density according to the Boussinesq model. The governing equations according to [1] are:

$$\nabla . \mathbf{u} = 0 \tag{1}$$

$$\rho_f (\mathbf{u} - \boldsymbol{w}). \nabla \mathbf{u} = -\nabla p + \mu_f \nabla^2 \mathbf{u} + \rho_f g_y \beta (T - T_c) \tag{2}$$

$$(\rho c_p)_f (\mathbf{u} - \boldsymbol{w}). \nabla T = k_f \nabla^2 T \tag{3}$$

$$\rho_s \ddot{\boldsymbol{d}}_s - \nabla \cdot \boldsymbol{\sigma}_s^{total} = \mathbf{f}_s^B \tag{4}$$

where $\ddot{\boldsymbol{d}}_s$ is the acceleration of the flexible wall, $\mathbf{f}_s^B$ is the body force, ρ_s is the density, u is the velocity vector, and $\boldsymbol{\sigma}_s$ is the stress. The following non-dimensional variables are utilized to write the equation in non-dimensional form.

$$X = \frac{x}{H}, \quad Y = \frac{y}{H}, \quad U = \frac{u}{u_o}, \quad V = \frac{v}{u_o},$$

$$P = \frac{p}{\rho_f u_0^2}, \theta = \frac{T - T_c}{T_h - T_c}, \ u_o = \frac{\alpha_f}{H}, \mathrm{u_o} = \mathrm{r_o} \omega_\mathrm{o}, \mathrm{Re} = \frac{\mathrm{u_o H}}{\nu}, \quad \mathrm{Gr} = \frac{\mathrm{g}\beta(\mathrm{T_H}\text{-}\mathrm{T_C})\mathrm{H}^3}{\nu^2}, \quad \mathrm{Pr} = \frac{\nu}{\alpha}$$

$$Ra = \frac{g\beta\Delta T H^3}{\nu_f \alpha_f} \quad , Pr = \frac{\nu_f}{\alpha_f} \tag{5}$$

The average Nusselt number along the hot wall is determined using the following equation:

$$\overline{Nu} = \frac{k}{\Delta T} \int \frac{\partial T}{\partial n} ds \tag{6}$$

The walls of the cavity are of nonslip velocity boundary condition. The outer walls are rigid and kept at high temperature T_h while the inner walls are flexible and kept at low temperature T_c. The short ends of the cavity are kept insulated as shown in Fig. 1. The Validation of results was presented in a previous study on the same project by Alshuraiaan [1]. COMSOL Multiphysics is used to analyze the problem and generate results.

3. Results and Discussion

The effect of Rayleigh number and the Young modulus of elasticity are considered in the analysis of results for the present study. Figure 2 shows the behaviour of streamlines for different values of Rayleigh number ($10^3<Ra<10^5$) at fixed value of the Young modulus of elasticity of 10^9 For both scenarios. For the case where the horizontal inner wall is flexible (left column), the variation of values of the stream function is higher than the ones for the other case (right column) where the horizontal inner wall is flexible. This figure shows that the first case has more circulation in the vertical zone which causes more heat transfer between the hot walls and the cold walls. The first row shows the results for a value of Rayleigh number of 10^3, the middle row shows the results for $Ra=10^4$ while the last row shows the results for $Ra=10^5$. It is evident that the deformation and the circulation of the fluid increase as the value of Rayleigh number increases.

The results of temperature isotherms of the two scenarios are shown in Fig. 3. The temperature gradient near the walls become steeper as Ra increases. The second scenario (flexible horizontal inner wall) results are shown in the left column of this figure. This scenario demonstrates steeper boundary layer next to the hot walls especially at the lower horizontal wall which in return cause more enhancement in the heat transfer process. It is important to notice that the deflection is highest for higher Rayleigh numbers which makes the hot and cold walls closer to each other and as a result the heat transfer process is enhanced. The isotherms are almost parallel for low Rayleigh numbers since the fluid circulation is not pronounced. The last row where $Ra=10^5$, one can notice that the isotherms are not parallel at the top part of the cavity as a result of more fluid circulation and enhanced heat transfer inside the cavity.

The average Nusselt number which represts the dimensionless temperature gradient at the hot walls is demonstrated in Fig. 4 for the range of $10^3<Ra<10^6$ at a fixed value for the modulus of elasticity at 10^9. Three different scenarios are shown in this figure which are, the first scenario (flexible vertical inner wall), the second scenario (flexible horizontal inner wall) and the fixed walls case. It is clear from Fig. 4 that the second scenario (flexible horizontal inner wall) has the highest Nusselt number values compared to the other two cases. For all of the three cases, the heat transfer increases as the Rayleigh number increases. Figure 5 presents results of the average Nusselt as a function of the modulus of elasticity ($10^8<E<10^{10}$) at fixed value of Rayleigh number ($Ra=10^4$). A lower Young's modulus of elasticity indicates a more elastic material that deforms easily. The Nusselt number is high for all three cases at low modulus of elasticity. The second scenario (flexible horizontal inner wall) has the highest Nusselt number values compared to the other two cases.

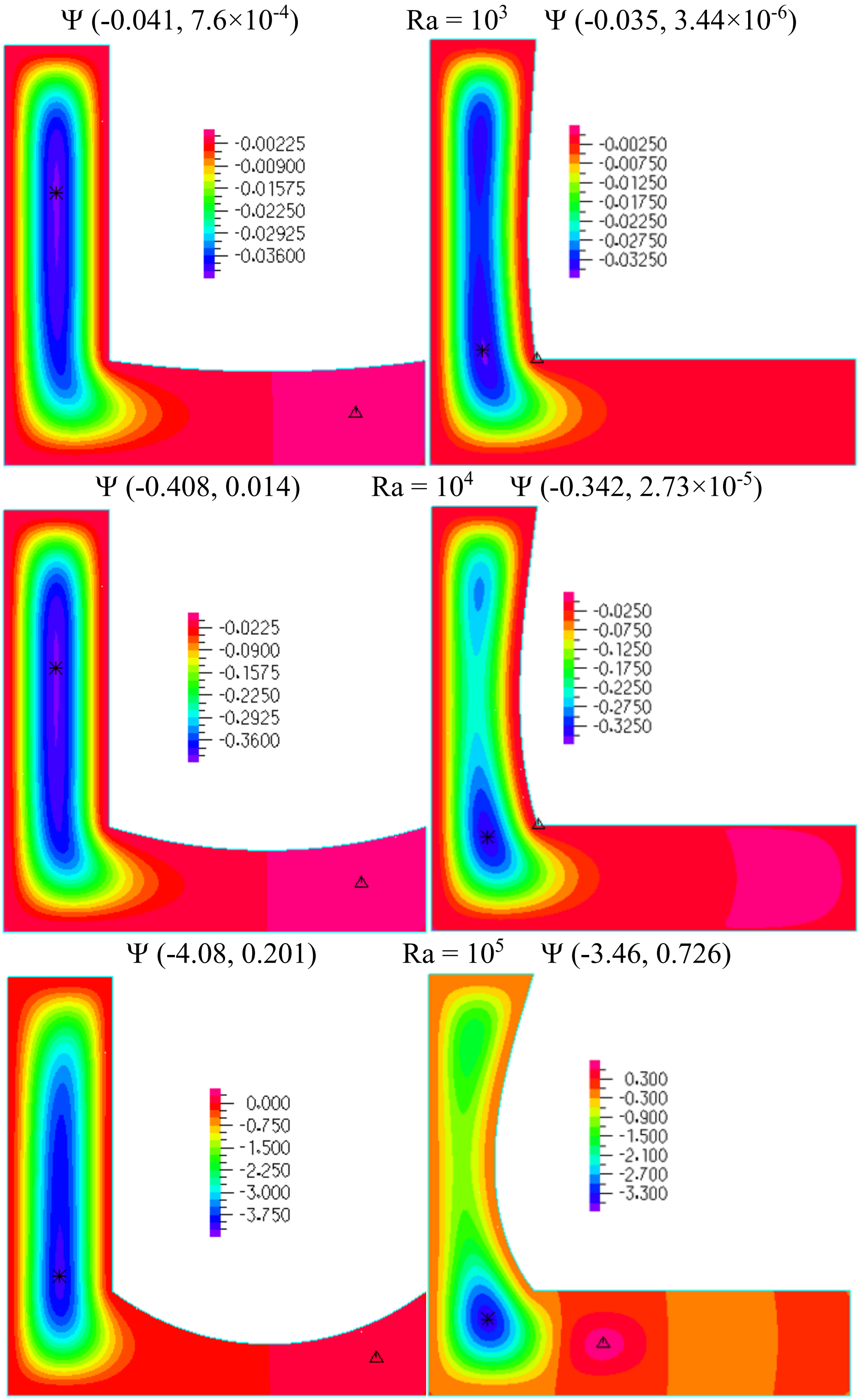

Figure 2. Comparison of the streamlines between different FSI scenarios inside L-shaped cavity for various Rayleigh numbers ($Pr = 0.7$, $E = 10^9$)

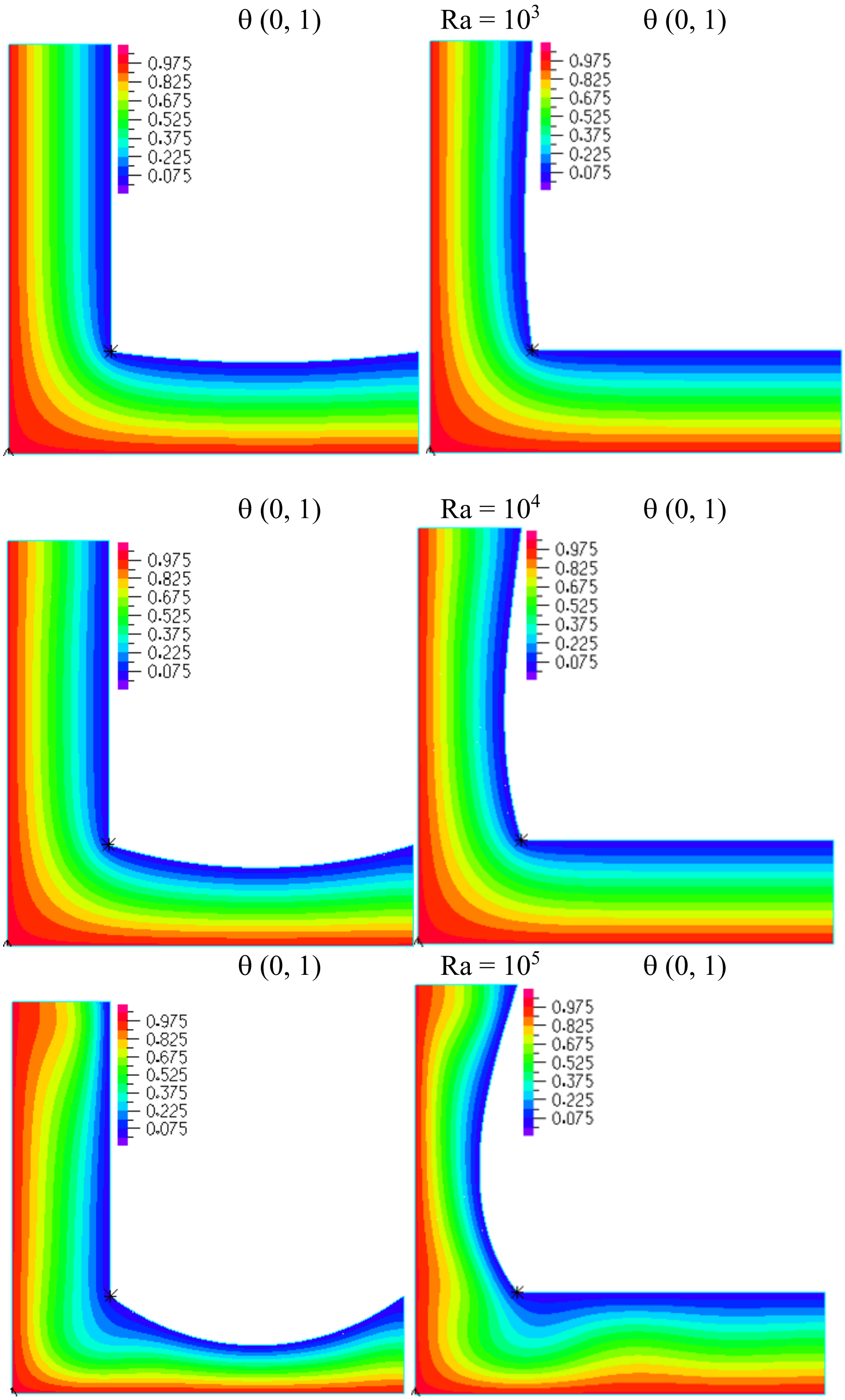

Figure 3. Comparison of the isotherms between different FSI scenarios inside L-shaped cavity for various Rayleigh numbers (Pr = 0.7, E = 10^9)

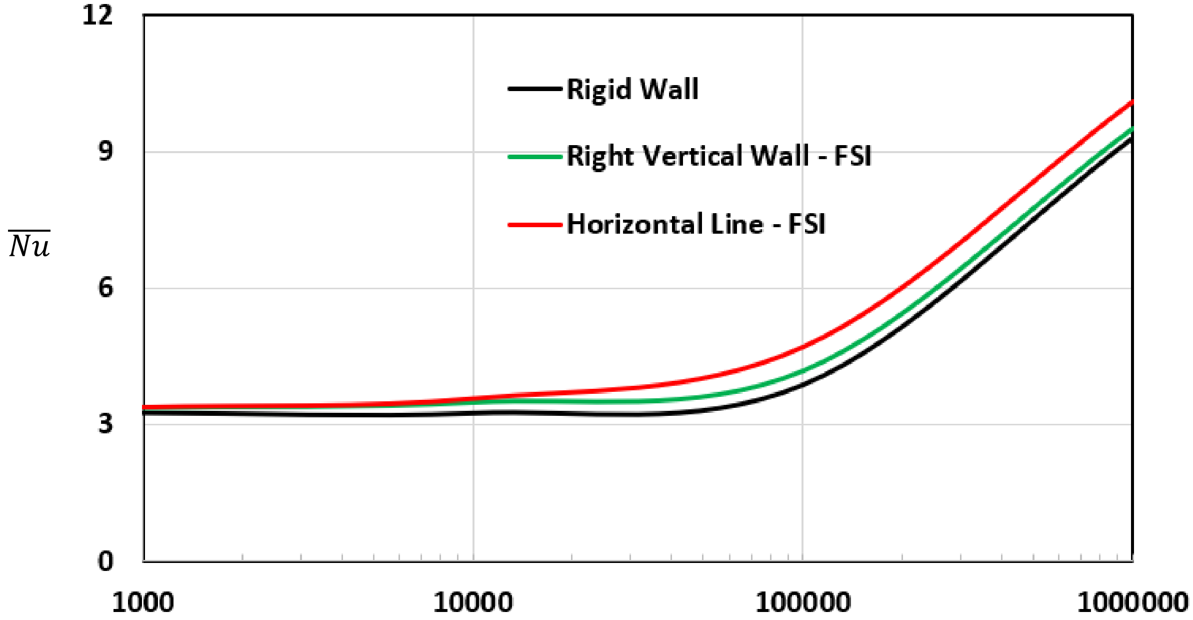

Figure 4. Comparison of the average Nusselt number between different wall models for various Rayleigh numbers (Pr = 0.7, E = 10^9)

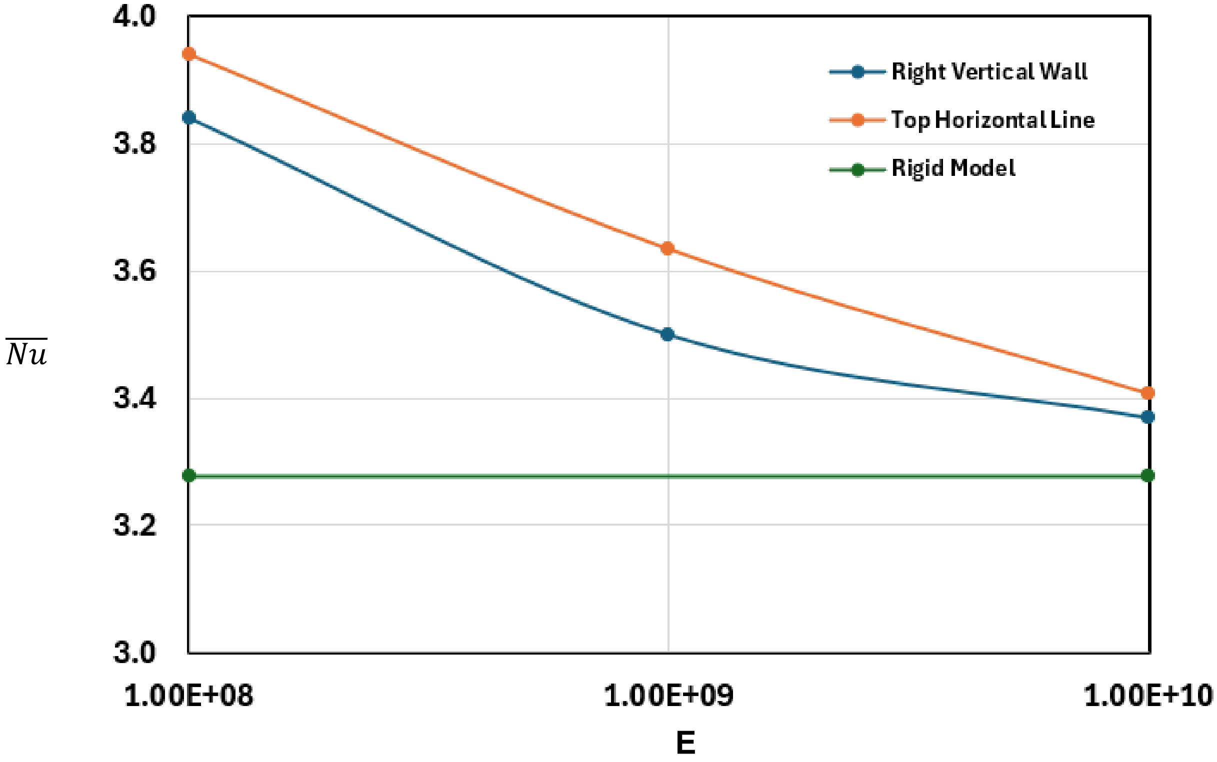

Figure 5. Effect of varying the elasticity of the wall on the average Nusselt number for various scenarios (Ra = 10^4, Pr = 0.7)

4. Conclusion

This work presents a numerical analysis of natural convection in an L-shaped cavity with flexible walls of the inner sides. Results suggest that as the Rayleigh number increases, buoyancy-driven convection intensifies within the L-shaped shaped cavity. This leads to better mixing and stronger flow circulation, resulting in an increased Nusselt number indicating indicating higher heat transfer efficiency. The stiffness of the solid boundary controlled by Young's modulus significantly significantly influences the interaction between the fluid and structure. A lower Young's modulus allows more deformation, enhancing the coupling between the fluid flow and the solid boundary. This can create dynamic flow patterns, further improving heat transfer. Conversely, a higher Young's modulus reduces boundary deformation, limiting FSI-induced enhancements but maintaining stability in heat transfer rates. The interplay between buoyancy forces characterized by the Rayleigh number and the structural deformation influenced by Young's modulus results in a non-linear enhancement in heat transfer. Optimizing both parameters can maximize the Nusselt number. The Nusselt number, being a measure of convective heat transfer relative to conduction, serves as an effective indicator. Higher Rayleigh numbers and appropriately tuned Young's modulus consistently yield increased Nusselt numbers. The findings underline the importance of considering FSI in thermal management system designs. By controlling material properties and operational conditions, heat transfer in complex geometries like L-shaped cavities can be significantly improved. Positioning of the flexible wall was found to have a significant impact on the heat transfer process.

Acknowledgements

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