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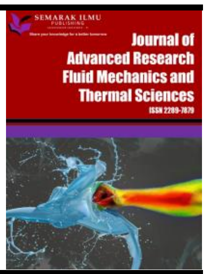

Fluid Structure Interaction Analysis of Natural Convective Flow and Heat Transfer in an L-Shaped Cavity

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ABSTRACT

The primary objective of this research work is to perform a numerical study on the fluid-structure interaction (FSI) of flow and heat transfer characteristics within an L-shaped cavity. The investigation will focus on analyzing the effects of various key variables, namely the Rayleigh number and wall elasticity, on the observed results. To accomplish this, the COMSOL software, which utilizes the finite element method, will be employed as the numerical simulation tool. To ensure the reliability and credibility of the obtained results, the findings of this research were rigorously validated against previously published data available in the literature. The outcomes of this investigation were presented using various visualization techniques. Streamlines, temperature contours, and heat transfer enhancement will be among the visual representations used to illustrate the flow and temperature distribution within the L-shaped cavity. Anticipated results indicated that the calculations of the average Nusselt number exhibited a strong dependency on the Rayleigh number and the wall elasticity. As such, the average Nusselt number was higher for flexible wall compared to rigid wall model. Moreover, the average Nusselt number was found to increase with an increase in Rayleigh number. Young's modulus was found to have a profound effect on the patterns of the streamlines. The average Nusselt number was found to decrease with an increase in the Young's modulus. This study may provide valuable insights into optimizing heat transfer and designing efficient thermal management systems for various practical applications.

1. Introduction

Extensive research has been conducted in the field of laminar natural convective flow and heat transfer within irregularly shaped enclosures, as evidenced by numerous studies documented in the literature. The reason behind the considerable attention given to this topic lies in its utmost importance across a wide range of applications, including solar collectors, electronics cooling, electrical equipment, and building corners [1-6]. In order to comprehend the intricate heat transfer characteristics, researchers have employed various types of enclosures in their investigations. These enclosure geometries encompass configurations with wavy surfaces, as well as those with triangular and trapezoidal shapes. Among the diverse range of enclosures studied, L-shaped enclosures have

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garnered significant interest within the scientific community due to their potential practical applications in electronics cooling and building design [7-10]. By examining these complex enclosure structures and analyzing their heat transfer properties, researchers aim to enhance our understanding of convective flow behavior and develop innovative strategies to optimize thermal management systems in numerous industrial and domestic settings.

In a study conducted by Tasnim and Mahmud [7], the flow and heat transfer characteristics within an inclined L-shaped enclosure were numerically investigated. The researchers examined the enclosure at various inclination angles and Rayleigh numbers using the finite volume method to discretize the governing equations. The results they obtained indicated that within the conduction-dominated zone, the average Nusselt number remained consistent and unaffected by variations in both the Rayleigh number and the inclination angle. However, within the convection-dominated zone, the average Nusselt number exhibited a linear trend when different inclination angles were considered. Another study by Saidi and Karimi [11] focused on the natural convection occurring in an L-shaped cavity containing water infused with Cu nanoparticles. The study investigated the impact of different Rayleigh numbers, nanoparticle concentrations, and the aspect ratio of the L-shaped cavity on the average Nusselt number. The findings demonstrated that incorporating nanoparticles led to improved heat transfer, resulting in an increase in the average Nusselt number. Additionally, Mahmoodi [8] conducted a numerical investigation to analyze the heat transfer characteristics within an L-shaped cavity filled with Cu-water nanofluid. SIMPLER algorithm was used in the numerical investigation. The outcomes showcased in that research exhibited that the heat transfer processes within the cavity escalated with higher Rayleigh numbers and the introduction of nanoparticles.

Recently, Moria [12] analyzed numerically the influence of porous layer and the position of heated blocks on the maximum heat transfer rate inside an L-shaped cavity. Bhopalam and Perumal [13] investigated the effect of Reynolds number and aspect ratio of cavity on flow characteristics inside an L-shaped lid-driven enclosure. Their findings demonstrated that the size of the recirculation zones was found to increase with an increase in Re.

Fluid-structure interaction (FSI) has recently garnered significant attention among researchers in literature. In a study conducted by Khanafer and Vafai [14], FSI was employed to analyze the behavior of porous media. Their results demonstrated that assuming a non-rigid wall condition led to an enhancement in the average Nusselt number. Similarly, Alsabery *et al.,* [15] examined the flow and heat transfer characteristics in a cavity with a non-rigid right-side wall. The findings of their study revealed that the non-rigid wall model exhibited higher rates of heat transfer compared to the rigid wall model, indicating the significance of considering wall flexibility in FSI simulations. In addition, Selimefendigil and Öztop [16] conducted a numerical study on Fluid-Structure Interaction (FSI) within a triangular enclosure filled with nanofluids. The results of their investigation showed a considerable enhancement in heat transfer performance within the enclosure when flexible walls were employed. Alshuraiaan and Pop [17] employed a deformable bottom wall in a trapezoidal cavity to enhance the mixed convection heat transfer with the presence of a hybrid nanofluid. Shahzad *et al.,* [18] studied the presence of elastic walls in wavy bifurcated channel with a bio-magnetic fluid. Their results show that the presence of the deformable walls reduces the wall shear stress all over the domain. Shahrulakmar *et al.,* [19] presented a systematic review of hemodynamic behavior in peripheral arterial diseases. Their study shows that the use of FSI is more realistic than using solid wall to resemble the arteries. This suggests that the interaction between the fluid and the deformable walls can lead to enhanced convective heat transfer, underscoring the importance of incorporating FSI effects in the design and analysis of such systems. The growing interest in FSI research reflects its potential in optimizing heat transfer processes and developing innovative solutions in various fields such as thermal management systems, engineering design, and advanced fluid dynamics.

The literature cited above highlights a notable observation that the fluid-structure interaction (FSI) of flow and heat transfer in an L-shaped enclosure with flexible walls has not been investigated previously. Motivated by this research gap, the objective of this work is to conduct a numerical analysis to explore and understand the impact of several key parameters on the average Nusselt number within the cavity. Specifically, the project aims to examine the influence of varying Rayleigh numbers and wall elasticity on the heat transfer characteristics. By undertaking this investigation, valuable insights can be gained regarding the interplay between the fluid flow, heat transfer, and the flexibility of the enclosure walls. Understanding the effects of these parameters on the average Nusselt number will contribute to the broader understanding of convective heat transfer within L-shaped enclosures with flexible boundaries. Moreover, the findings from this work can have practical implications for the design and optimization of systems involving L-shaped enclosures, such as electronics cooling, building insulation, and various industrial applications. Ultimately, this research endeavor aims to expand our knowledge and provide a foundation for further advancements in the field of fluid-structure interaction and heat transfer within irregular-shaped enclosures.

2. Methodology

The scenario being studied is illustrated in Figure 1. The investigation involves the analysis of two-dimensional, incompressible, steady, and laminar flow as well as heat transfer within the L-shaped cavity. The dimensions of the L-shaped enclosure are such that its height (H) matches its width (W). In this context, the left side of the enclosure maintains a constant temperature T_H, which is higher than the temperature T_C on the L-shaped side, as depicted in Figure 1. While all other surfaces are treated as adiabatic, the working fluid within the cavity is air, characterized by a Prandtl number (Pr) of 0.7. Throughout the analysis, the physical properties of the fluid are assumed to remain constant, with the exception of density variations that are accounted for using the Boussinesq model.

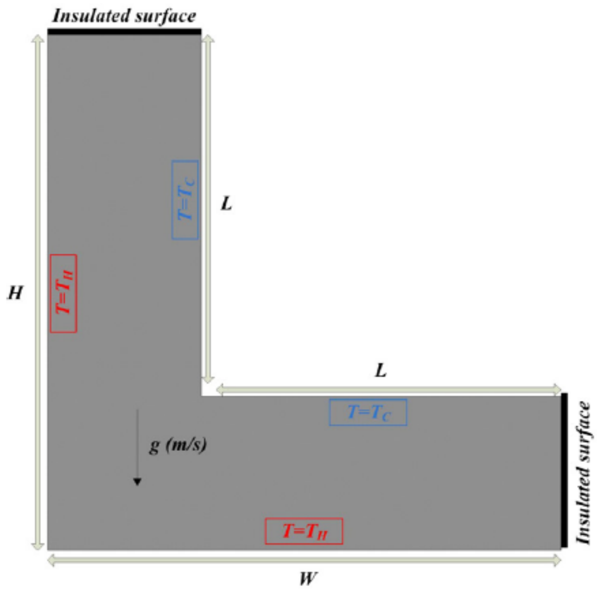


Fig. 1. Schematic of the problem under investigation and boundary conditions

The governing equations used in this investigation are given by [14,17]:

<u>Continuity</u>

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

<u>Momentum</u>

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

<u>Energy</u>

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

The following equation is used to model the flexible was as follows [14,17]:

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

where $\ddot{\boldsymbol{d}}_s$ is the acceleration of the flexible wall, $\mathbf{f}_s^{\mathbf{B}}$ 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.

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

$$P = \frac{p}{\rho_f u_0^2}, \theta = \frac{T - T_c}{T_h - T_c}, u_o = \frac{\alpha_f}{H},$$

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

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

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

2.1 Numerical Scheme

The Galerkin-weighted residual approach within the finite element method framework is used to address the partial nonlinear governing equations (Eq. (1) to Eq. (4)) in this research. The software 'COMSOL 5.4' is utilized for this study, harnessing its Multiphysics capability to handle fluid-structure interaction. This software also accommodates the necessary dynamic mesh adjustments due to the presence of a flexible bottom wall. The computational process employs an unstructured mesh composed of triangular elements. This mesh configuration includes finer elements around the cavity's center and even finer elements along the boundaries. To ensure the reliability of the computations, a grid independence analysis is conducted. A mesh size of 241 by 241 is chosen based on this analysis, demonstrating satisfactory outcomes. The chosen mesh size meets a convergence threshold with an error magnitude of less than 10^{-6}, especially for velocity and temperature, even at high Rayleigh numbers.

2.2 Code Validation

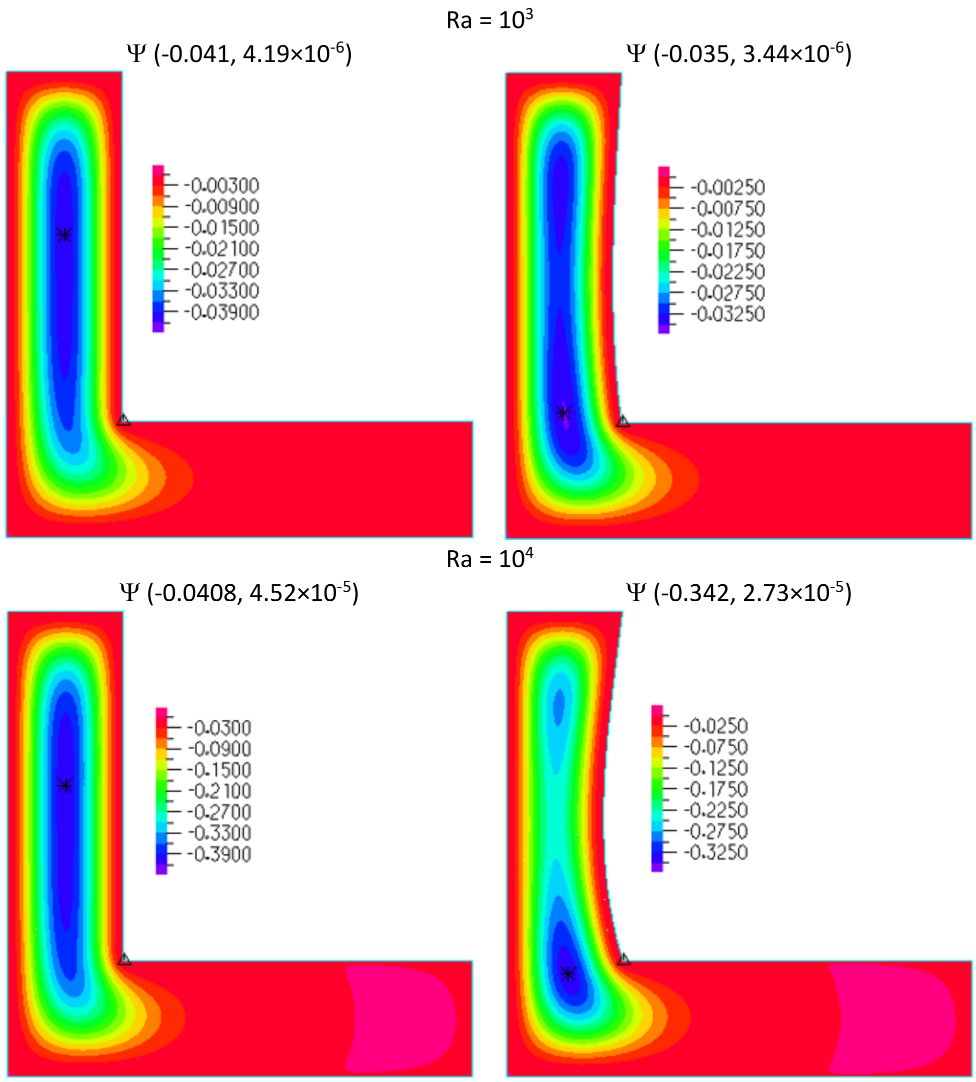
To validate the accuracy of the current numerical method, multiple investigations that centered on rigid walls were employed. The comparison of average Nusselt numbers within the L-shaped enclosure for various Rayleigh numbers is displayed in Table 1. This table exhibits a strong correlation between the outcomes of the present study and the findings from previously documented research [7,8,11].

Table 1
Comparison of the average Nusselt number at the hot walls of an L-shaped enclosure filled with air

	Tasnim and Mahmud [7]	Mahmoodi [8]	Saidi and Karimi [11]	Present
Ra = 10^3	3.25	3.27	3.27	3.27
Ra = 10^4	3.26	3.26	3.26	3.28
Ra = 10^5	3.90	3.86	3.91	3.88
Ra = 10^6	9.33	9.34	9.23	9.33

3. Results and Discussion

The observations and comparisons of the varying Rayleigh numbers on the streamlines and isotherms for the rigid and flexible wall models are illustrated in Figure 2 and Figure 3. Figure 2 provides insights into the behavior of the streamlines for both models at different Rayleigh numbers. At low Rayleigh numbers, it can be observed that the streamlines for both the rigid and flexible wall models exhibit similar patterns. The flow appears relatively uniform and steady within the cavity. However, as the Rayleigh number increases, indicating higher temperature differences, the intensity of convection becomes more pronounced. This leads to significant changes in the flow patterns. As the Rayleigh number reaches Ra = 10^4, an interesting phenomenon occurs in the flexible wall model. The initial distinctive large eddy present within the flow undergoes a fascinating transformation, fragmenting into two smaller-scale eddies that exhibit distinctive characteristics. This interesting phenomenon unfolds as one of these newly formed eddies takes shape in the vicinity of the upper horizontal wall, while the other finds its existence closer to the lower wall of the enclosure. The intricate process of this eddy division can be linked to the complex interaction between the flow dynamics and the flexibility of the enclosure's walls. The mechanism behind this breakup becomes even more captivating when considering the behavior of the flexible wall. This wall, due to its flexibility, exhibits a distinct response to the thermal forces present within the system. Specifically, it undergoes a noticeable bulging motion towards the vertical hot wall. This localized bulging serves as a dynamic force that directly influences the flow patterns within the enclosure. As the flexible wall's bulging action interacts with the fluid motion, it effectively influences the redistribution of energy and momentum within the system. This intricate interplay ultimately leads to the division of the original large eddy into the two smaller ones. Such a phenomenon illustrates the nuanced interconnections between fluid dynamics and structural flexibility, highlighting how the characteristics of an enclosure can remarkably alter the behavior of fluid flows within it. The flexibility of the wall allows for the redistribution of fluid flow, leading to the formation of these smaller eddies. In contrast, the rigid wall model maintains a large eddy occupying a significant portion of the vertical section of the L-shaped cavity. Continuing to higher Rayleigh numbers, Figure 2 reveals additional changes in the flexible wall model. The right flexible wall bulges inward even more, influencing the flow dynamics within the cavity. This bulging effect causes the smaller eddy near the top horizontal wall to disappear. The fluid circulation within the cavity becomes more vigorous due to the increased deformation of the flexible wall. In contrast, the rigid wall model remains relatively unaffected, with the large eddy continuing to dominate the vertical section of the L-shaped cavity. Importantly, Figure 2 also indicates that both models exhibit nearly stagnant flow in the horizontal section. This stagnant behavior is likely due to the geometric configuration of the cavity and the interaction between the streamlines and the walls.



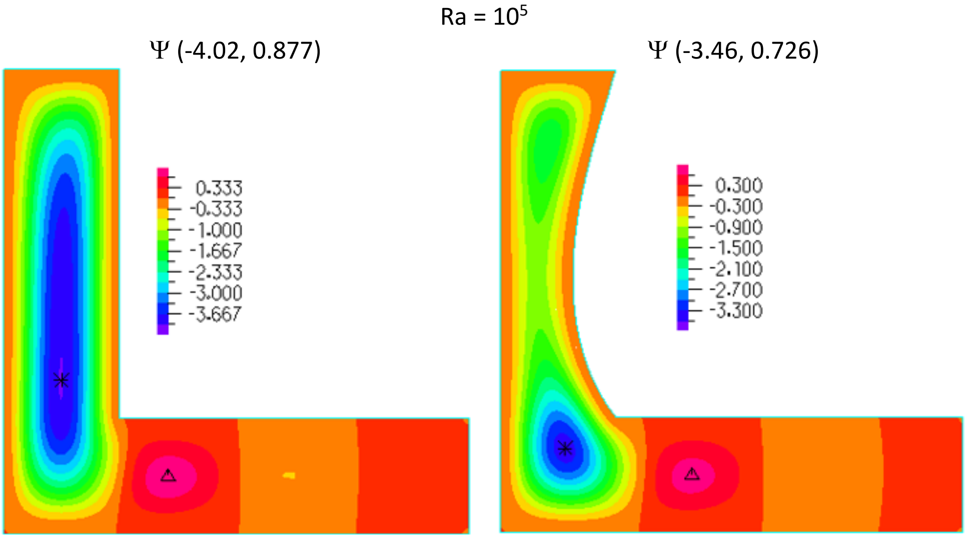


Fig. 2. Comparison of the streamlines between rigid and flexible wall models inside L-shaped cavity for various Rayleigh numbers (Pr = 0.7, E = 10^9)

Figure 3 describes the impact of varying Rayleigh numbers on the distribution of isotherms. The visualization highlights distinct behaviors within the isotherms under different conditions. At lower Rayleigh numbers, specifically 10^3 and 10^4, both models display isotherms that run in parallel, indicative of heat transfer primarily driven by conduction mechanisms. However, a notable shift in behavior is observed as the Rayleigh number escalates to 10^5. The isotherms exhibit signs of disruption, signalling a significant transition from conduction-based heat transfer to the prevalence of free convection as the dominant heat transfer mode. Remarkably, Figure 3 clearly depicts a more pronounced disruption of the isotherms in the flexible wall model when compared to the rigid wall model. In conclusion, the comparison of streamlines and isotherms at different Rayleigh numbers between the rigid and flexible wall models reveals substantial distinctions in the flow patterns and fluid behavior. The flexibility of the wall introduces complexities, resulting in the formation and disappearance of smaller eddies, while the rigid wall maintains a consistent large eddy presence. These observations highlight the influence of wall flexibility on the fluid flow dynamics and the importance of considering such factors in understanding the behavior of convective systems.

Figure 4 provides supporting evidence for the advantageous role of employing a flexible wall in improving heat transfer compared to the rigid wall model. The average Nusselt number is calculated for both models, and the results are displayed in Figure 4. The figure clearly indicates that the flexible wall model consistently yields higher average Nusselt numbers across different Rayleigh numbers. The effect of Rayleigh numbers on the x-deformation of the right flexible wall is depicted in Figure 5. As Rayleigh numbers increase, the wall bulges significantly inward causing the flow to accelerate in the vertical section and consequently enhances heat transfer. The effect of varying the Young's modulus of the flexible wall on the streamlines and isotherms is illustrated in Figure 6. It is clear from Figure 6 that the inward bulging of the wall decreases with an increase in the Young's modulus. Moreover, it is shown that Young's modulus has a profound effect on the streamlines structure. As the Young's modulus increases, the two separate eddies merged to form one large eddy occupying the vertical section of the cavity. This is due to the expansion effect.

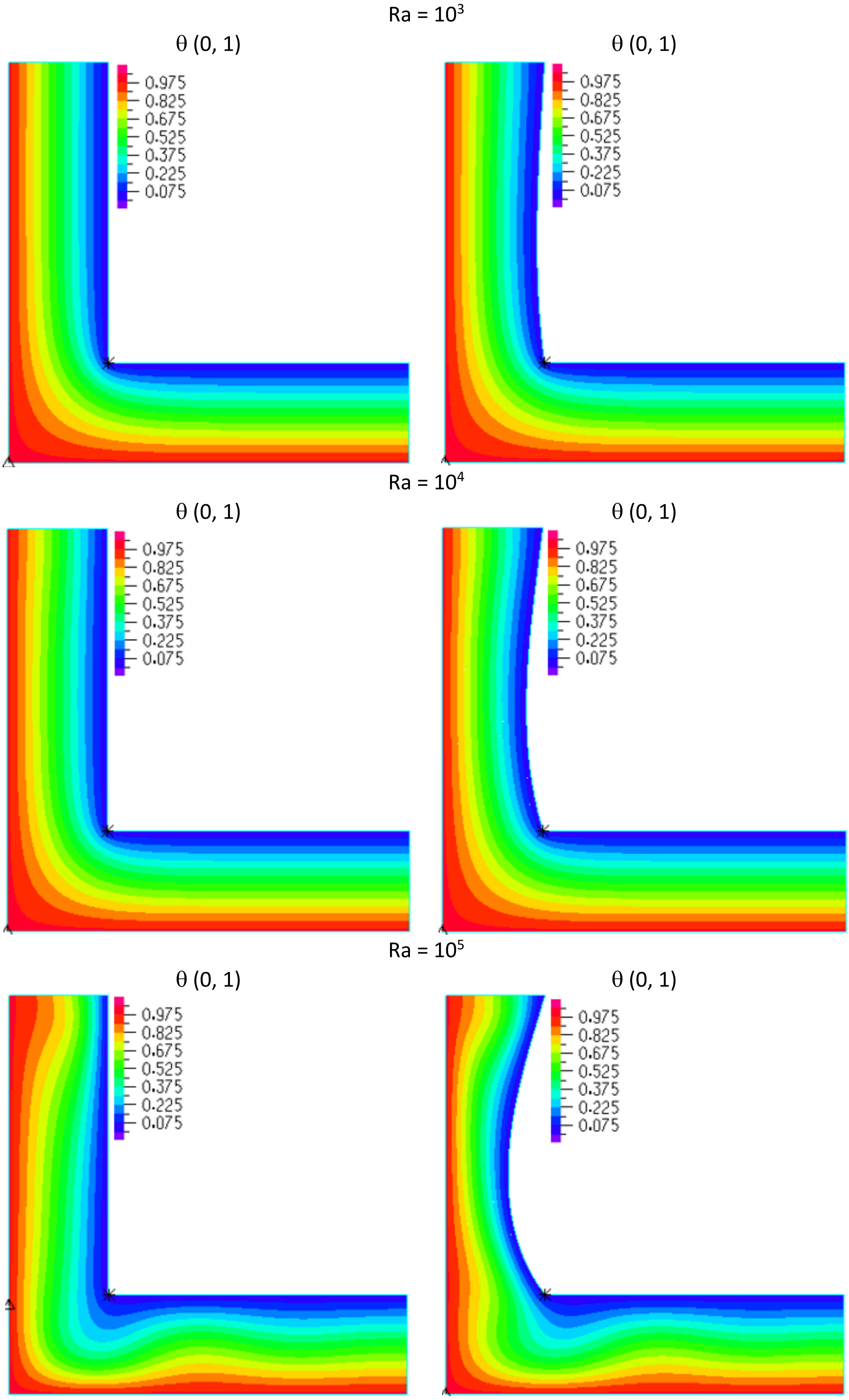


Fig. 3. Comparison of the isotherms between rigid and flexible wall models inside L-shaped cavity for various Rayleigh numbers (Pr = 0.7, E = 10^9)

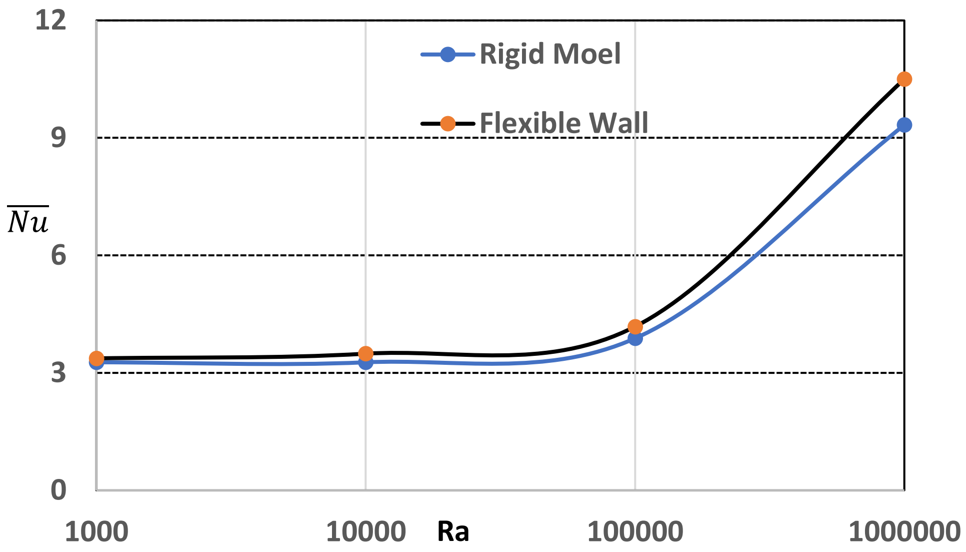


Fig. 4. Effect of varying the Rayleigh numbers on the average Nusselt number (Pr = 0.7, E = 10^9)

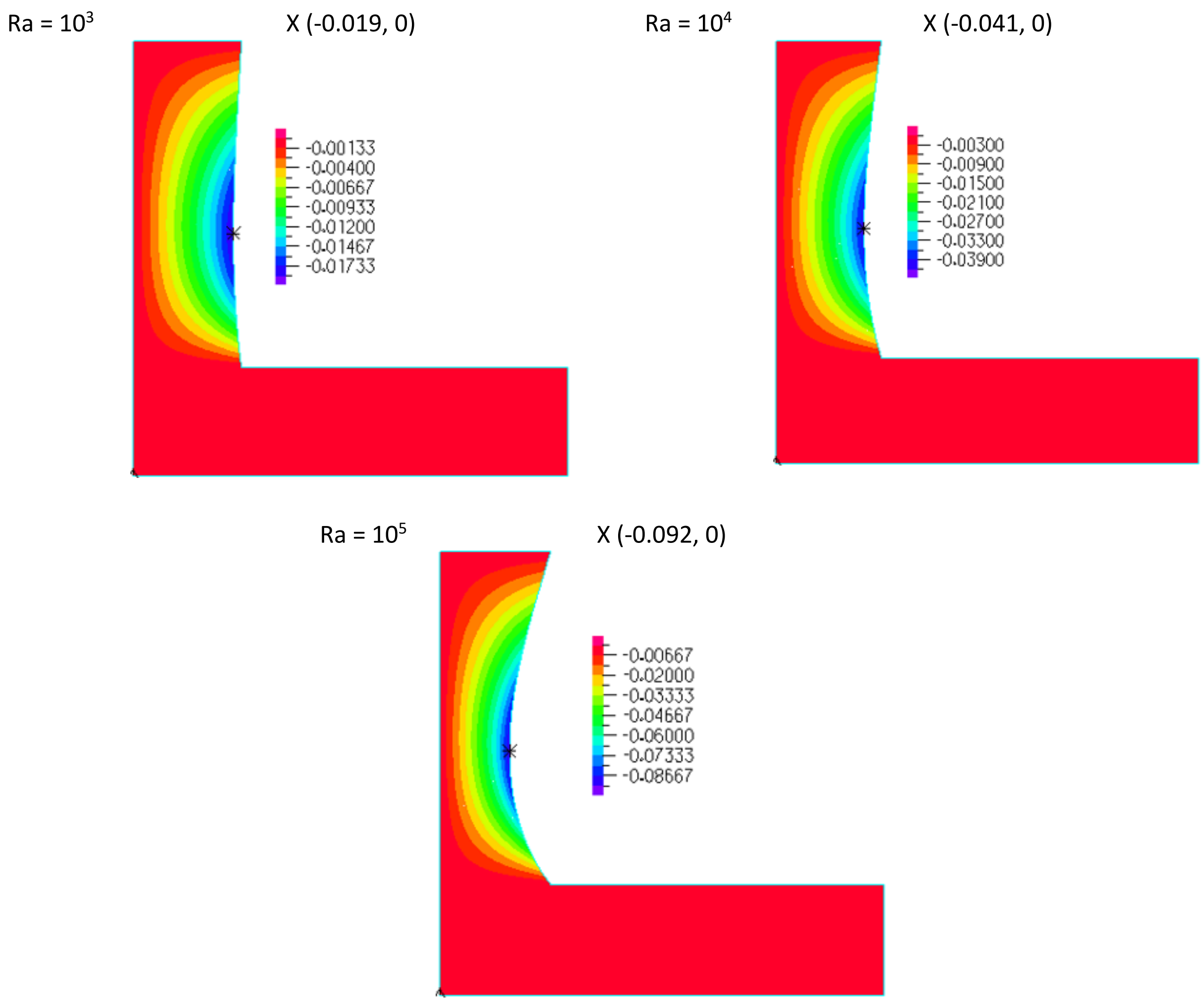


Fig. 5. Effect of varying Rayleigh number on X-displacement (Pr = 0.7, E = 10^9)

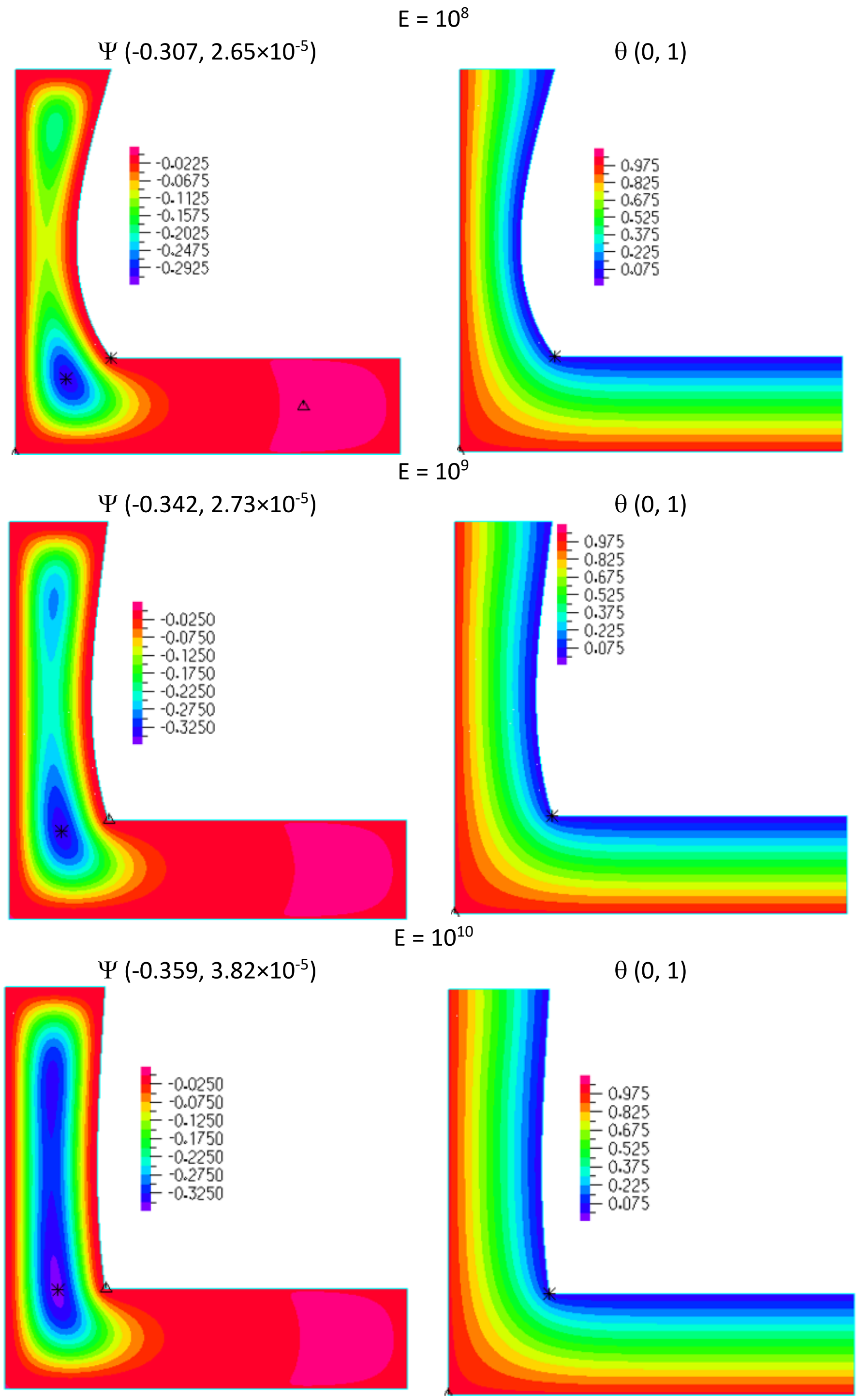


Fig. 6. Effect of varying the non-dimensional Young's modulus on streamlines and isotherms (Pr = 0.7, Ra = 10^4)

4. Conclusions

A comprehensive numerical investigation was undertaken to delve into the intricacies of fluid-structure interaction within an L-shaped enclosure, operating under conditions of natural convection. This analytical endeavor encompassed a broad spectrum of scenarios, considering a range of Rayleigh numbers and diverse Young's modulus values. To illuminate the underlying phenomena, the acquired data were translated into insightful visual representations through the depiction of streamlines, isotherms, and the computation of average Nusselt numbers. The intriguing aspect that emerged from this study was the discernible impact of the flexible wall model in contrast to the rigid wall model. This dynamic became particularly pronounced as the investigation progressed, revealing that the flexible wall model consistently exhibited higher average Nusselt numbers compared to its rigid counterpart. This intriguing observation underlines the pivotal role that the wall's flexibility plays in influencing heat transfer dynamics within such enclosures.

Further intricacies were unraveled by the study's scrutiny of Young's modulus. It became evident that this material property had a discerning influence on the intricate patterns depicted by the streamlines, which are suggestive of the fluid motion within the enclosure. Simultaneously, the heat transfer phenomena within the cavity were found to be significantly swayed by variations in Young's modulus. In the larger context, these findings shed light on a promising avenue for enhancing heat transfer processes, as demonstrated by the potential application of flexible walls. This insight not only contributes to the academic understanding of fluid-structure interactions but also holds implications for practical engineering applications, where optimizing heat exchange mechanisms is of paramount importance.

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