Investigating the Effect of Flexible Fins on Natural Convection In a Newtonian Fluid

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Abstract: This study examines the impact of fluid-structure interaction on the natural convection occurring within a square cavity. The cavity is equipped with a square bar with two flexible fins, the temperature of the left vertical wall is high, while the right wall is low. The upper and lower walls of the cavity are highly insulated, the square bar with two elastic fins to the Centre cavity. The Newtonian fluid flows within the cavity as a result of buoyancy forces. The numerical simulation employs a finite element method incorporating an arbitrary Lagrangian-Eulerian (ALE) framework. The study investigates the impact of Rayleigh number 1E3<Ra<1E5, dimensionless elasticity modulus 5E9<Eτ<1E11. The findings indicate that the local and average Nusselt numbers increase when the Ra value rises with the elasticity modulus. We note the role of flexible fins in improving heat transfer and increasing fluid mixing, unlike rigid fins that act as an obstacle to fluid movement and thus reduce heat transfer.

Keywords: fluid-structure interaction, flexible fin, Newtonian fluid, cavity, convection natural.

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1. INTRODUCTION

Convective heat transfer plays a vital role in a wide range of engineering applications, including cooling electronic equipment and constructing efficient heat exchangers. Although forced convection is generally efficient in transferring heat, its dependence on external energy input makes it less preferable in some circumstances. As a result, there has been considerable scientific interest in improving natural convection while yet keeping it passive. These solutions involve the use of baffles, the integration of fins or barriers, and the use of nanofluids (Webb et al., 2005). Thanks to recent developments in materials research, flexible structures have emerged as a novel method for controlling heat transport. These structures, such as fins or membranes, undergo deformation due to hydrodynamic forces, which affect flow patterns, boundary layer thickness, and heat transfer properties (J Ismael et al., 2019). This literature review explicitly examines the developing topic of fluid-structure interaction (FSI) in natural convection within cavities, with a particular focus on using flexible structures to promote heat transmission. Initial investigations on Free Surface Instability (FSI) in natural convection examined the effects of pliable fins affixed to the hollow walls (Ghalambaz et al., 2017).They examined the impact of a pliable fin that moves back and forth in a wave-like pattern on the heated surface of a square enclosure. Their research revealed that using a flexible fin improves the process of transferring heat compared to a rigid fin. Moreover, this improvement is further intensified by increasing the amplitude of the oscillation. In the same way (Ismael et al., 2018).The study showcased the efficacy of a free-end flexible fin in managing the thermal boundary layer And enhancing heat transmission in a ventilated enclosure. Subsequent investigations examined the impact of pliable barriers on natural convection (Raisi et al., 2018). Investigated a square hollow featuring a pliable upper wall and a pliable baffle, illustrating that the associated distortions contribute to energy storage and release, resulting in improved fluid circulation and heat transfer. Research on cavities with flexible partitions has demonstrated the substantial influence of partition deformation on flow patterns and heat transmission properties (Amini, 2016; Yaseen, 2020; Ghelardi, 2017; Chen, 2018).

This study examines how the flexible fin affects heat transfer by natural convection in a confined space. Gaining a comprehensive understanding of this correlation is essential for maximizing the efficiency of thermal management systems, particularly in scenarios with restricted forced convection, such as in electronics cooling or solar thermal collectors.

2. MODELING APPROACH

The geometry in this investigation, as seen in Figure 1, the square cavity is equipped with a square bar with two flexible fins. The square cavity has dimensions of L^* It is occupied by a fluid that follows Newton's laws of flow. The flexible fin bends due to the buoyancy force generated by natural convection.

The left and right walls are considered to have a specific temperature T_h^* and T_c^*, whereas the top and bottom walls are thermally insulated. The no-slip requirement applies to all the walls, including the hollow's exterior walls and the fin's surfaces. The flexible fin is regarded as having uniform thickness t_{fin}^{*} and isotropic properties. The temperature disparities were presumed to be restricted. Therefore, the thermophysical characteristics were assumed to be unaffected by temperature, except the liquid's density, which was accounted for using the Boussinesq model.

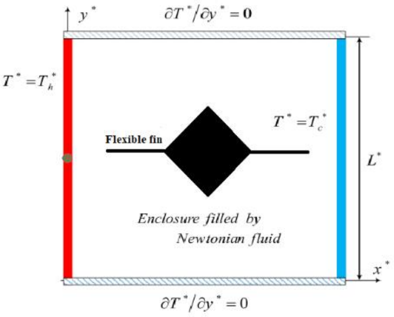

Figure 1. Schematic of problem definition.

The issue's hydrodynamic and thermal properties are modeled using the Arbitrary Lagrangian-Eulerian (ALE) approach, based on the assumptions given previously. The equations representing these characteristics are shown below.

Momentum equations:

$$\nabla^{*} \cdot u^{*} = 0 \tag{1}$$

$$\rho f\left[\frac{\partial u^{*}}{\partial t}+\left(u^{*}-w^{*}\right)\cdot\nabla^{*}u^{*}\right]-\nabla^{*}\cdot\left[-P^{*}I+\mu\left(\nabla^{*}u^{*}+\left(\nabla^{*}u^{*}\right)^{tr}\right)\right]-\rho_f\beta g\left(T^{*}-Tc^{*}\right)=0 \tag{2}$$

The energy equation for the fluid:

$$\left(\rho c_p\right)_f\left[\frac{\partial T^{*}}{\partial t}+\left(u^{*}-w^{*}\right)\cdot\nabla^{*}T^{*}\right]-k_f\nabla^{*2}T^{*}=0 \tag{3}$$

The energy equation for the flexible fin:

$$\left(\rho c_p\right)_s\frac{\partial T^{*}}{\partial t}-k_s\nabla^{*2}T^{*}=0 \tag{4}$$

The boundary conditions imposed on the outer walls and the interface between the flexible fin and the Newtonian fluid may be expressed as follows: at the heated wall:

$$\left(F_v=0\right) \tag{5-a}$$

At the cold wall:

$$T=0,\ u=v=0 \tag{5-b}$$

At the upper and lower walls:

$$\frac{\partial T}{\partial y}=0,\ u=v=0 \tag{5-c}$$

3. RESULTS AND DISCUSSION

This section investigates the impact of various factors on the thermo-flow fields and the deformation of the flexible fin. The variable parameters refer to the elasticity modulus. $\left(5\times10^{9}\le E\tau\le10^{11}\right)$,Rayleigh number $\left(10^{3}\le Ra\le10^{5}\right)$,while the other important parameters like the dimensionless body force $\left(F_v=0\right)$,the plate's thickness$\left(t_{fin}=0.01\right)$ thermal conductivity ratio $\left(k_r=100\right)$, Prandtl number $\left(Pr=10\right)$ and density ratio $\left(\rho_R=1\right)$ are considered constant during the numerical simulations.

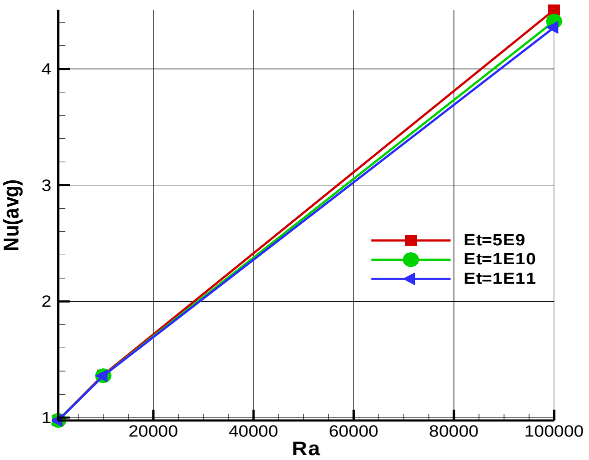

Figure 2. Variation of the average Nusselt number with Rayleigh numbers for different values of E_τ and Pr=10.

As the Rayleigh number increases, the average Nusselt number also increases. This suggests that a more robust buoyancy-driven flow (higher Ra) results in more efficient convective heat transfer. An elastic modulus value of $E_\tau=5E9$ is also considered optimal for achieving a high average Nusselt number.

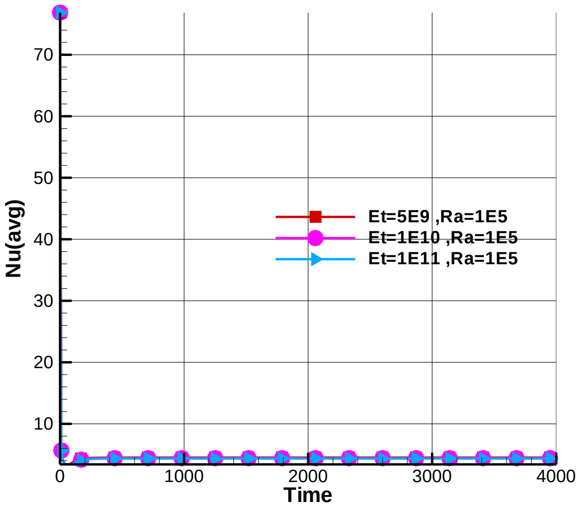

Figure 3. Development of the average Nusselt number with time for different values of E_τ, $Ra=10^5$ and Pr=10.

The average Nusselt number at the primary dimensionless time steps. This is because of the negligible natural convection in comparison with the conduction. Steady state after a certain period, the temperature and velocity profiles reach a stable state. At this point, the average Nusselt number becomes relatively constant, no longer changing with time.

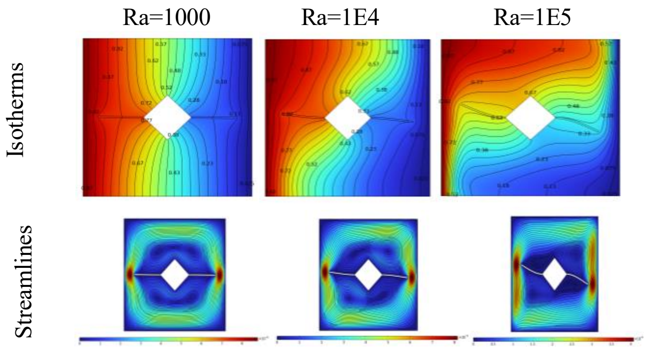

Figure 4. Streamlines and isotherms for different values of Ra, $E_{\tau} = 5E9$ and Pr = 10.

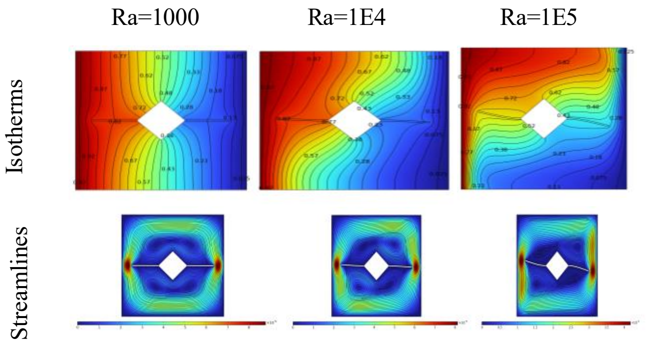

Figure 5. Streamlines and isotherms for different values of Ra, $E_{\tau} = 1E10$ and Pr = 10.

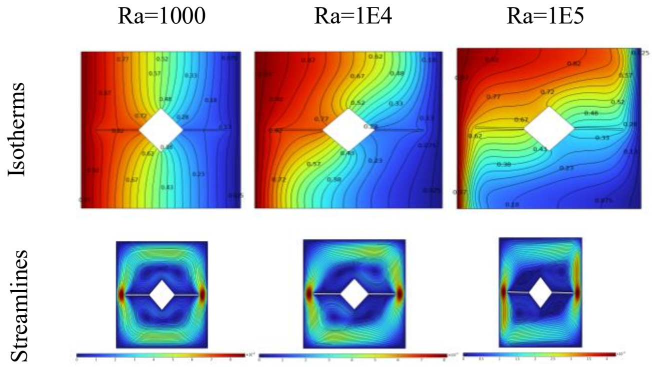

Figure 6. Streamlines and isotherms for different values of Ra, $E_{\tau} = 1E11$ and Pr = 10.

Figures 4,5, and 6 Illustrate the impact of Rayleigh number and various elasticity modulus values on the isotherms and streamlines under steady-state conditions for Eτ and Pr = 10. The fin does not experience any displacement at the lowest Rayleigh number (Ra= 1E3). Furthermore, the vertical stratification of the isotherms determines this specific Rayleigh number. The relationship between higher Ra and higher buoyant force is apparent. At a Rayleigh number (Ra) of (Ra= 1E4), the intensified buoyancy force leads to increased fluid motion and a faster heat transfer rate. At this specific Rayleigh number, there is a slight upward movement of the fin for (Eτ=5E9) and (Eτ=1E10). When (Eτ=5E9) and (Ra=1E5), the enhanced buoyancy forces significantly disrupt the region above the fin.

Show the impact of elasticity modulus (Eτ) and various Rayleigh number (Ra) values on the isotherms and streamlines. A rise in Eτ leads to an increase in the resistance of the fin against stress, resulting in a decrease in the displacement of the fin.

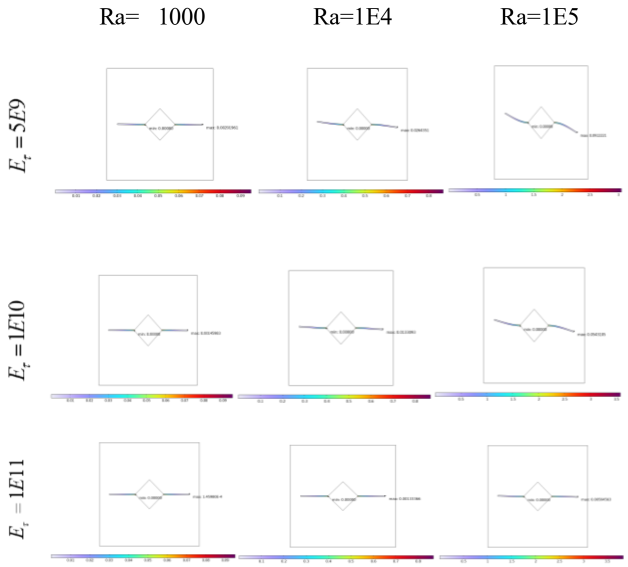

Figure 7. The maximum values of stress on the fin for different values of Ra, Eτ and Pr = 10.

A high Rayleigh number significantly impacts the deformation of an elastic fin with an elasticity value of $E_{\tau} = 5E9$. However, a fin with an elasticity value of $E_{\tau} = 1E11$ remains rigid and unaffected by the Rayleigh number, as it is weakly elastic.

4. CONCLUSIONS

This study comprehensively investigated the influence of Rayleigh number (Ra) and elasticity modulus (Eτ) on natural convection within a cavity. The square bar with two elastic fins to the Centre cavity were analyzed under specific conditions, and Prandtl number (Pr), revealing the intricate interplay between fin placement, flow patterns, and heat transfer characteristics.

1- The buoyancy forces generated by natural convection cause the flexible fin to bend, affecting the flow dynamics.

2- The Nusselt average number increases with the Rayleigh number, and a larger Rayleigh number indicates a more significant impact of buoyancy, resulting in enhanced natural convection and heat transmission.

3-A flexible fin fixed at specific locations in a cavity filled with a Newtonian fluid alters the flow patterns، heat transfer rates، and stress distribution within the system، showcasing the complex interplay between fluid dynamics and structural deformation.

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