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ENTROPY GENERATION FOR NATURAL CONVECTION DUE TO HEAT TRANSFER IN AN INCLINED CAVITY

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Abstract

The thermal control in many systems is widely accomplished applying mixed convection process due to its low cost, reliability and easy maintenance. Typical applications include the aircraft electronic equipment, rotating-disc heat exchangers, turbo machinery, and nuclear reactors, etc. Natural convection in an inclined square enclosure heated via wall heater has been studied numerically. Finite volume method is used for solving momentum and energy equations in the form of stream function–vorticity. The right and left walls are kept at a constant temperature, while the other parts are adiabatic. The range of the inclination angle covers a whole revolution. The method is validated for a vertical cavity. A general power law dependence of the Nusselt number with respect to the Rayleigh number with the coefficient and exponent as functions of the inclination angle is presented. For a fixed Rayleigh number, the inclination angle increases or decreases is found.

Keywords: *Natural convection in enclosure, inclined enclosure, Nusselt number.*

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I. INTRODUCTION

The heat transfer due to natural convection of air in rectangular or square enclosure filled with different fluids or fluid saturated porous media has received considerable attention in the last three decades due to its wide application in the area of engineering. These application areas include the cooling of electronic devices, double-pane windows, heating and cooling of building and so on. A wide review was performed by Ostrach [1]. The studies on natural convection in enclosure focus on mainly differentially heated enclosure in the literature. A wide documentation related to this subject is available in the study of Vahl Davis and Jones [3]. After that, different boundary conditions were applied for cavities, such as the enclosure heated from bottom and cooled from vertical walls while top wall has insulation [4], the enclosure heated and cooled on adjacent walls [5] and the enclosure with L-shaped corners with adiabatic and cold isothermal horizontal walls [6].

Natural convection of air in a square cavity with two differentially heated opposite walls and the other two adiabatic is numerically studied by Huelsz and Rechtman [2], for the laminar regime as both the Rayleigh number and the inclination angle of the cavity change.

A detailed study of the laminar solution of the problem (Ra up to lo3) was given by Barakos et al [7] results covering a wide range of Rayleigh numbers. Many correlations of Nusselt number (Nu) concerning experimental results can also be found in this paper. Markatos and Valor [8,9] studied a laminar model in their calculations. They performed two-dimensional simulations for Rayleigh numbers up to 10^3 and presented a complete set of graphs for different values of Ra (Pr = 0.71), including isotherms, streamlines and velocity fields.

In recent years, partial heaters were used on the wall of enclosure to simulate the flush mounted electronic heaters which have isothermal or constant heat flux. Chu et al. [10] studied the natural convection in an enclosure with a partial heater located to the left vertical wall and the enclosure cooled from right vertical wall. They investigated the problem both numerically and experimentally. Chao et al. [11] investigated the natural convection in a tilted enclosure with the half of the lower surface heated and the other half insulated both experimentally and numerically. It was observed that the asymmetry due to insulating half of the heated surface resulted in circulations. They observed that both the location and the length of the heater are important parameters on flow and temperature field. Different configurations of these types of heaters in both discretely and partially heated form can be found in [12–13]. Recently, Nithyadevi et al. [14] performed a numerical work to analyze the natural convection heat transfer in a rectangular enclosure partially heated and cooled from vertical walls. The observed results in their study are very similar to study of Turkoglu and Yucel [15], except for aspect ratio. They used control volume method with power scheme and SOR technique to discretized the governing equations. They found that heat transfer increases with the increase of aspect ratio. In the present study, our main aim is to investigate the effects of the inclination angle on the natural convection in a square cavity at different Rayleigh number. The effect of inclination of the enclosure on the development of flow structure and the transport process is presented and discussed. These types of computers work at different inclination angles on humans hands and in different environmental conditions such as inside the car, outside the room, even in the garden of a school or a house**.**

II. PHYSICAL MODEL

Natural convection inside a two-dimensional inclined square cavity of side H = W as shown in Fig.1 is the object of study. Two opposite walls are conductive at temperatures T_H and T_C and the other two walls are adiabatic. The inclination angle φ is such that φ = 0° when the two conductive walls are perpendicular to the acceleration of gravity g with the bottom one at temperature T_H. The inclination angle increases counterclockwise and decreases clockwise.

The range of φ covers a whole revolution from -180° to 180°.

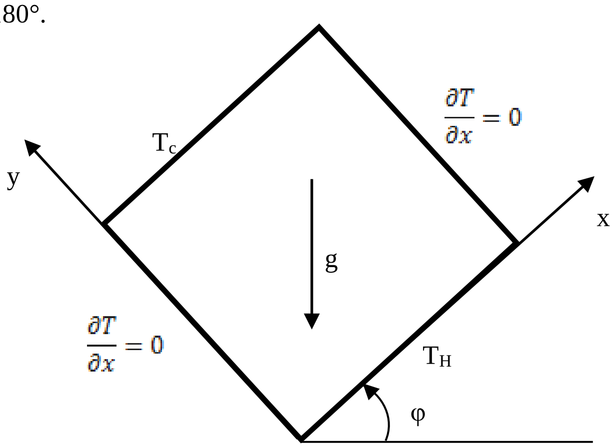

Fig. 1. Square cavity showing the inclination angle φ and the walls at temperatures ($T_H > T_C$).

III. MATHEMATICAL MODEL AND NUMERICAL PROCEDURE

The governing equations were solved by a software package Fluent 6.3.26. The Power Law scheme was used to evaluate the diffusive and convective fluxes at the interface of each control volume. The SIMPLE algorithm is used to treat the coupling pressure-speed. The discretization grid is obtained for uniform elements of 5184 nodes.

IV. CODE VALIDATIONS

The results are compared with Huelsz and Rechtman [2], where the comparison regarding the Temperature fields and streamlines for different inclination angles with fixed Raleigh number (as shown in figure 2).

Moreover, another numerical study for validation results have been performed for the case of isothermally heated square enclosure, and found to agree quite well number (as shown in figure 3).

Figure 3 displays the average Nusselt number at the heat source surface for different configurations. The investigations are carried for different inclination angles -180° < φ < 180°.

As can be seen from figure 3, Nusselt numbers are the Increased with increasing of inclination angles at -180° < φ < 90° as expected. There is symmetry with respect to a change in the sign of φ, since such a change will only alter the direction of the fluid flow as shown in Figures 1-3. For each value of the inclination angle there is a maximum Nusselt number Nu_{max} which occurs at an angle φmax. It is found that $Nu_{max} = 4.68$ at $Ra = 10^5$ and φ = 90°. Also, it has a minimum value around -180° and 180°at the same Rayleigh number. For $Ra = 10^3$, Nusselt values are almost the same. It means that vertical heater makes little effect on heat transfer when a wider heater is used for the first case, due to the domination of the conduction mode of heat transfer. Higher Nusselt number is formed for higher Rayleigh number.

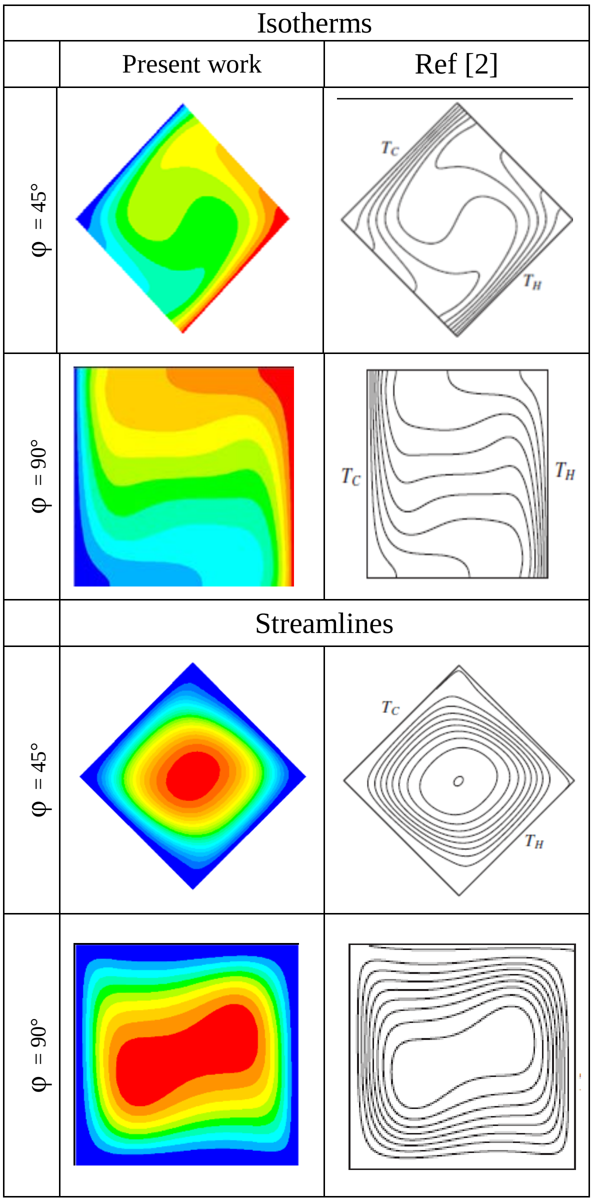

Fig. 2. Temperature fields and streamlines for different inclination angles (Newtonian fluid)

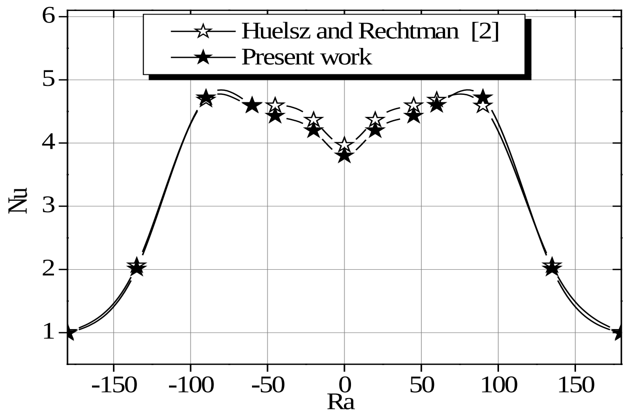

Fig. 3. The Nusselt number Nu for Newtonian fluid as a function of the inclination angle φ increments for fixed values of the Rayleigh number ($Ra = 10^5$).

V. RESULTS AND DISCUSSION

In the present work, results were obtained for natural convective flow for Pr = 0.71 and Gr = 105, using a uniform rectangular mesh. The Rayleigh number, in the range 103 ≤ Ra ≤ 10^5 at different inclination angle. The objective of this study is to examine the heat transfer characteristics due to natural convection of Newtonian fluid inside a square cavity with two differentially heated opposite walls and the other two adiabatic. The resulting flow structure is analyzed to provide a fundamental understanding of the effect of angle inclination and Rayleigh number on the thermal flow. Important dimensionless parameter for the present study is the overall Nusselt number, on which the effect of varying the inclination angle in the whole range 0° < φ < 135°.

a. streamlines and Temperature profiles at Ra = 10^3

The steady state temperature field and streamlines for Newtonian fluid at fixed Rayleigh number (Ra = 10^3) are shown in Figure 4.

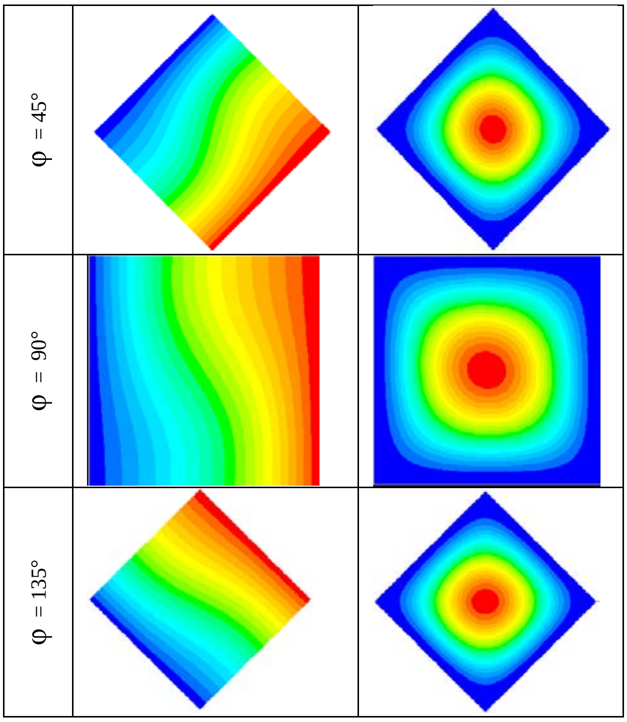

Fig. 4. Isotherms and streamlines for 45°≤φ≤135° at Ra= 10^3

The numerically calculated flow field for Newtonian fluid (see the streamline diagram of Figure 4) indicated that one secondary cell, in the centre of the square cavity. Meanwhile, the intrusion flow of the concentration layer has just passed each corner in its forward movement along both the heaters source. As this flow gradually reduces, the cavity fluid becomes increasingly stratified. This is due to the fact that most of the horizontal intrusion emerging from the boundary layer accumulates along the horizontal wall and forms a thin layer near the heat wall. When the inclination angle increases, the first big cell can occupy the entire cavity.

b. Streamlines and Temperature profiles at Ra = 10^4

Laminar flow visualization for the transient development of the heat transfer for different inclination angles (φ = 45°, 90°, 135°) with Ra = 10^4 is shown in Figure 5. Note that when the inclination angle increases, the heavier fluid descends along the heat wall. Note a very strong upward flow near the opposite side. Since the Nusselt number in this system is higher than the last case. An examination of Figure 5 reveals that once the left hand vertical boundary layer flow reaches the top corner for increasing inclination angle, the flow rebounds slightly in its horizontal movement across to the opposite wall.

At φ = 135°, note that the outer upward (downward) layer flow severely rebounds away from the upper left wall and moves downwards. However, the flow moves forward along both the top and the bottom cavity, eventually forming stratified layers in these regions once it reaches the opposite walls. Note that the fluid in this region moves very slowly along in the horizontal direction, enlarging with expelling the rotation of flow in the core.

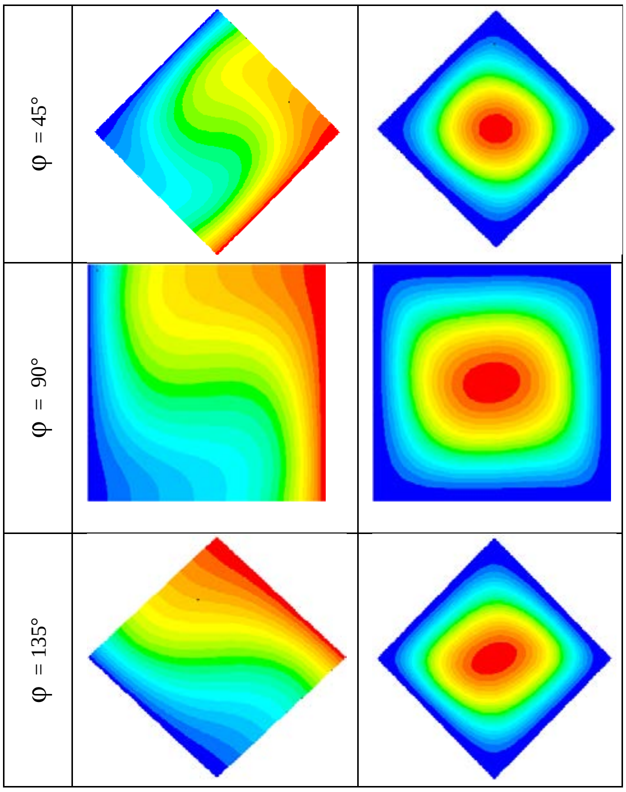

Fig. 5. Isotherms and streamlines for 45°≤φ≤135° at Ra= 10^4

c. Entropy generation

Figure 6 shows the total entropy generation number with the Rayleigh number at different inclination angles for Newtonian fluid in the square cavity.

The entropy generation number increases with an increasing Rayleigh number, particularly in the region next to the cavity wall. This is because of the enhancement of heat transfer rates with the increasing inclination angles. The entropy generation number increases almost linearly at high Rayleigh numbers. This is due to the temperature gradients, which do not change much radially, conduction heat transfer due to temperature gradient is low, resulting in less entropy generation in this region).

The results obtained from the parametric investigation of entropy generation in the enclosure are useful when designing the flow system. In this case, a different inclination angle results in a high rate of entropy generation in the flow system, which requires high Rayleigh number to overcome the heat transfer power. However, this situation is tolerable for a certain range of Rayleigh number ($0 \leq Ra \leq 10^6$).

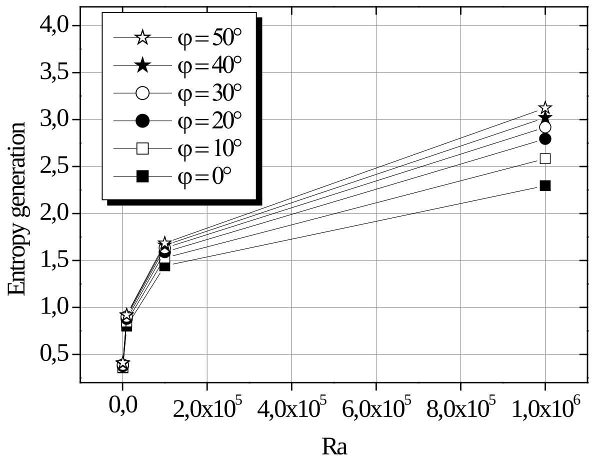

Fig. 6. Entropy generation as a function of the Rayleigh number Ra increments for different values of the inclination angles φ = 0° to 50°.

VI. CONCLUSION

A steady, two-dimensional numerical analysis of natural convection heat transfer and fluid flow in an inclined square cavity with two heating sources has been performed. It is observed that the heat transfer and entropy generation are an increasing function of Rayleigh number. The effect of inclination angle is particularly strong in the upstream regions on the isothermal walls due to heat transfer and entropy generation. The variation of the inclination and Rayleigh number of the enclosure can change the entire flow structure significantly. Entropy generation value is a maximum for a Rayleigh number (103) of around φ = 0° at the first case (φ = 0°) and a minimum for φ = 135°.

No remarkable change for entropy generation at low inclination angles, but higher heat transfer was formed. Rayleigh number affects the heat transfer especially at critical inclination angle of the enclosure. The study can be used for instability analysis and second law analysis of thermodynamics for higher Rayleigh number in a separate study in the future.

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