Entropy Generation Analyze Due to the Steady Natural Convection of Newtonian Fluid in a Square Enclosure

T. T. Naas, Y. Lasbet, C. Kezrane

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**—**Inclined enclosure, natural convection in enclosure, Nusselt number.

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 [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 [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 [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 [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.

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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, [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 [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.

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 with $T_H > T_C$ and the other two are adiabatic. The inclination angle φ is such that $\varphi = 0°$ 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°.

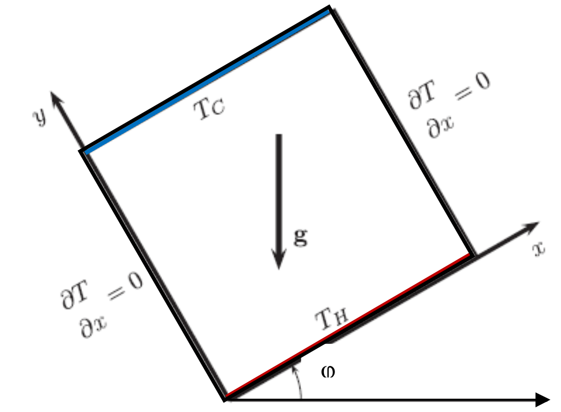

Fig. 1 Square cavity showing the inclination angle g and the walls at temperatures T_H and T_C ($T_H > T_C$): The other two walls are adiabatic. The x and y axes rotate with g

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

Fig. 2 presents a case validation for this work, where the comparison regarding the temperature fields and streamlines for different inclination angles with fixed Raleigh number.

Moreover, another numerical study for validation results have been performed for the case of isothermally heated square enclosure, and found to agree quite well, where the comparison regarding the effect of Richardson number on the average of Nusselt number.

Fig. 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 Fig. 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 Figs. 1-3. For each value of the inclination angle there is a maximum Nusselt number Nu_{max} which occurs at an angle φ_{max}. 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.

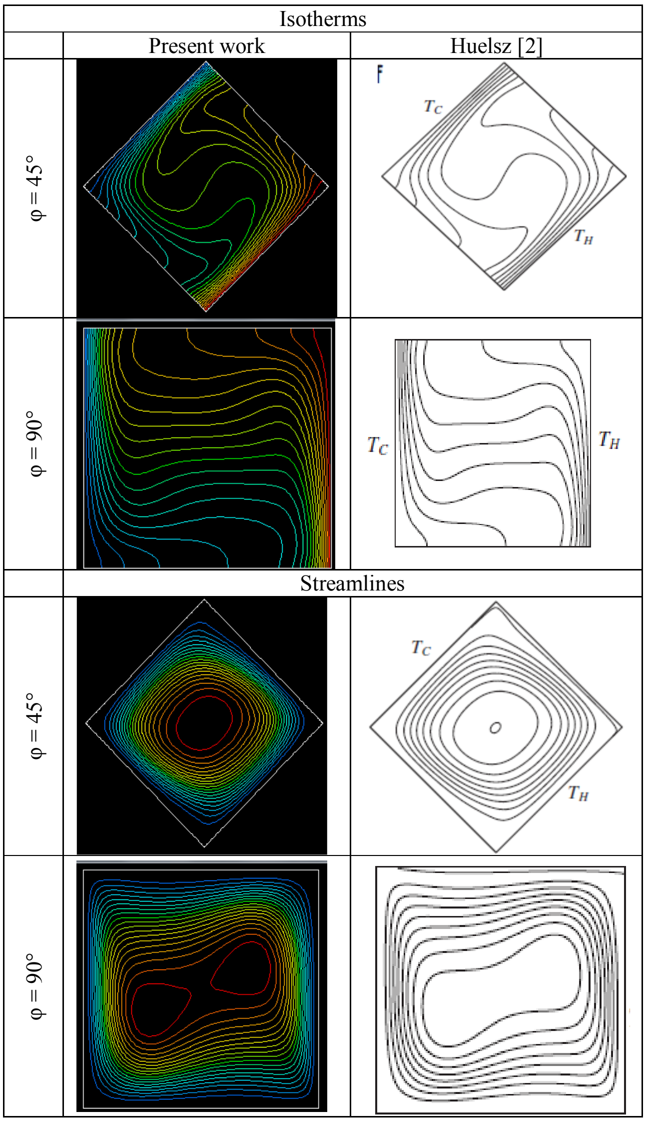

Fig. 2 Isotherms and streamlines for different inclination angle (φ = 45°, φ = 90°) at fixed Rayleigh number ($Ra = 10^5$)

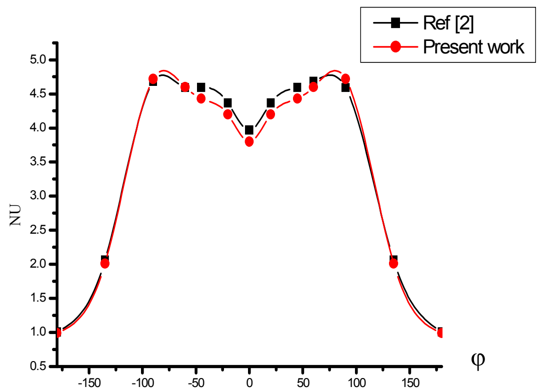

Fig. 3 The Nusselt number Nu as a function of the inclination angle φ increments for fixed values of the Rayleigh number ($Ra = 10^5$)

V. Results and Discussion

In the present work, results were obtained for natural convective flow for several values of Rayleigh number $10^3 \leq Ra \leq 10^6$, using a uniform rectangular mesh. The objective of this study is to examine the heat transfer characteristics due to natural convection 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 flow and thermal. 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 -180° <φ< 180°.

A. φ = 45°, 90°, 135° and Ra = 10^3

For the first results, the initial state is one with constant density and a conductive temperature field. The steady state temperature field and the corresponding streamlines are shown in Fig. 4 for several values of Rayleigh (Ra = 10^3, 10^4, 10^5) with different inclination angles.

The numerically calculated flow field at Ra = 10^3 (see the streamline diagram of Fig. 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. φ = 45°, 90°, 135° and Ra = 10^4

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 Fig. 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 Fig. 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.

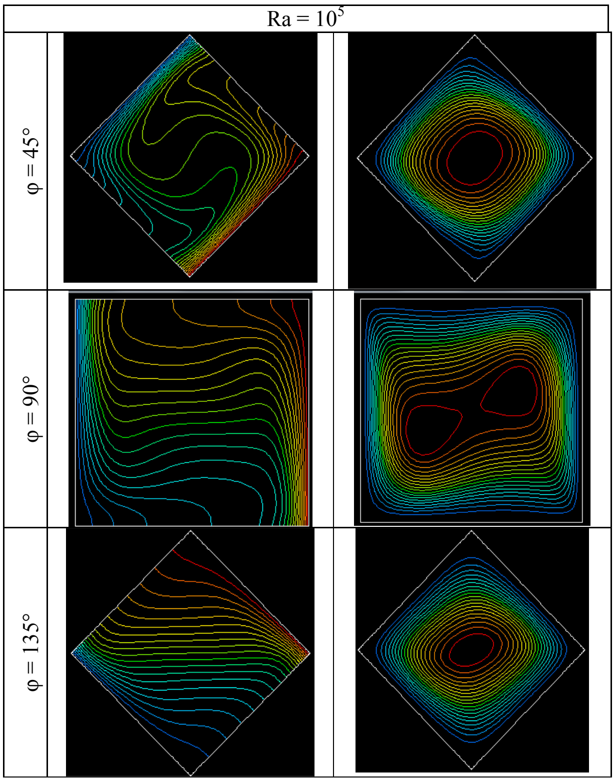

Fig. 4 Isotherms and streamlines for 45°≤φ≤135° at Ra= 10^3

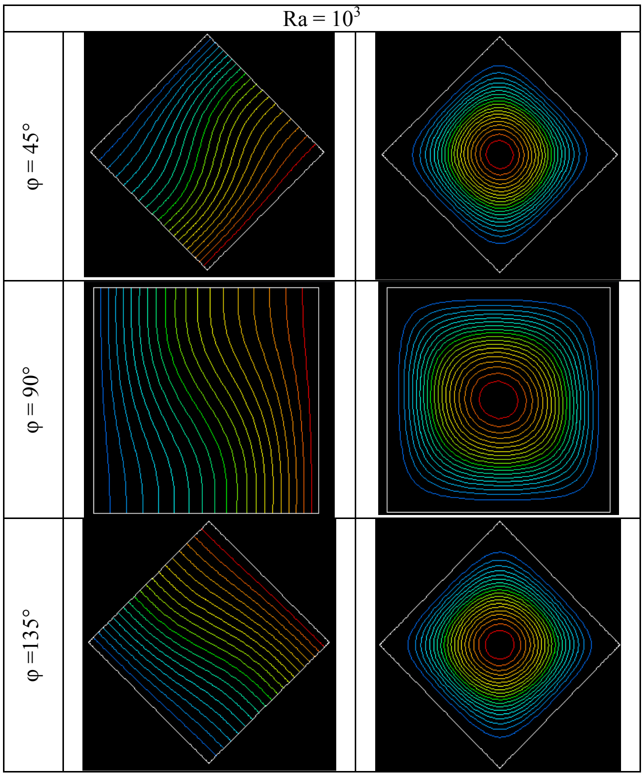

Fig. 5 Isotherms and streamlines for 45° ≤φ ≤135° at Ra= 10^4

C. φ = 45°, 90°, 135° and Ra = 10^5

Fig. 6 illustrates a series of numerical results for different inclination angle φ = 45°, 90°, 135° for a flow structure with Ra = 10^6. The observed flow structures together with simulated flow field and concentration distribution diagrams are discussed.

At φ = 45° as shown in Fig. 6, the two secondary cells in the corners have merged and formed a large clockwise cell. The large clockwise cell in this instance, forms in a completely different manner from that mentioned previously (φ = 45°, Ra = 10^5).

In this case, the heavier (higher) intrusion flow fluid at the bottom (top) moving from the cooler wall is carried to the top (bottom) plate by the viscous boundary layer flow and instead of immediately rebounding downwards (upwards) after hitting this surface, it continues forward along the upper (bottom) plate for a distance, curving back down (up) to form a clockwise cell. The flow structure in this initial stage is similar to that reported by [16] in a side-heated enclosure filled with water for Ra = 3.26 * 10^8 at φ = 90°. In the current system, however, a concentration stratified region in both the upper and the lower corner of the enclosure can be formed, which becomes thicker with times and maintains stagnant.

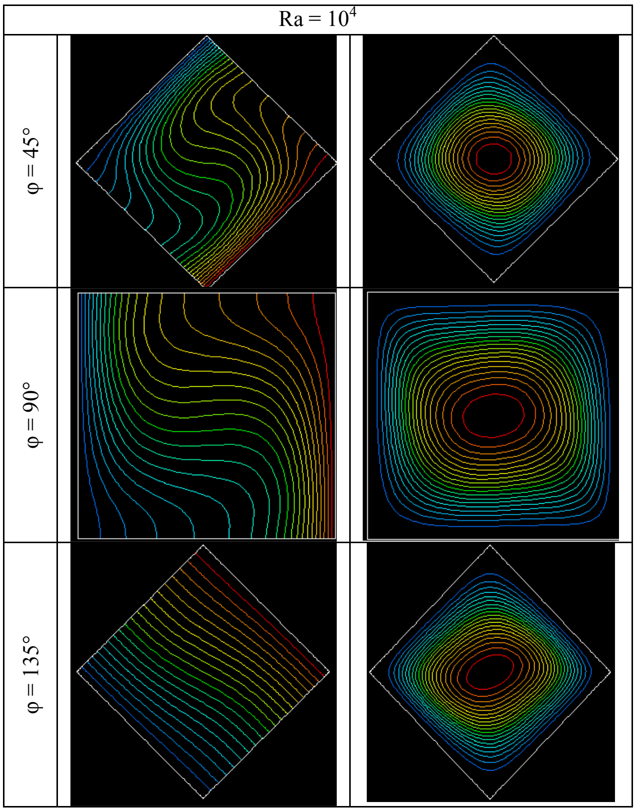

Fig. 6 Isotherms and streamlines for 45° ≤φ≤ 135° at Ra= 10^5

VI. Entropy Generation (S) for Different Inclination Angles

Fig. 7 shows the total entropy generation number with the Rayleigh number at different inclination angles 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 air cavity flow 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 air parameter and Rayleigh number (<10^6).

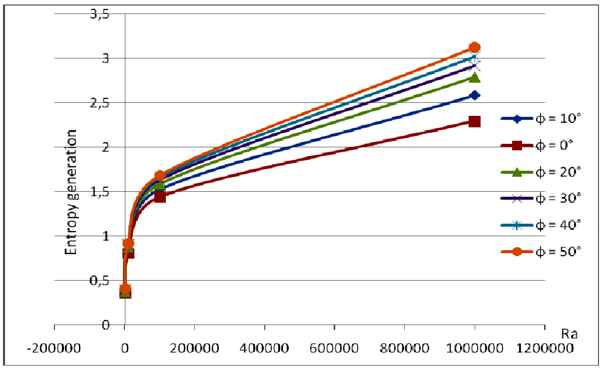

Fig. 7 Entropy generation as a function of the Rayleigh number Ra increments for different values of the inclination angles φ = 0° to 50°.

VII. 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 (10^6) of around φ = 50° and a minimum for φ = 0°.

No remarkable change for entropy generation at low inclination angles (φ <10°), 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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