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Natural Convection and Flow Simulation in Right-Angled Triangular Rooftop Enclosure under Winter Condition

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***Abstract*:** *In this study,natural convection and flow simulation in right-angled triangular rooftop enclosure when heated isothermally from the base wall (winter condition) are examined using ANSYS FLUENT as the design modeler. The effects of Rayleigh number, pitch angle, and the heating side on the flow structure and temperature distribution within the enclosure are investigated. Convection currents are noticed as the air rises from the hot base towards the cold roof forming plumes. The heat transfer within the enclosure reduces with increase in pitch angles. At low pitch angle, multiple heat flow circulations with high intensity between the cold inclined wall and hot base wall results in multicellular flow structure within the enclosure. But as the pitch angles and Rayleigh number increases, the number of cells reduces as small cells emerged to form bigger ones, which shows proper mix of air within the enclosure.The practical significance of the results is that the flow patterns and thermal characteristics of the attic space presented will be of a great value to professionals engaged in design and analysis of building attics, to ensure proper functions of the attics and its energy efficiency.*

Key Words: *Natural convection, Pitch angle, Right-angled triangular roof shape, ANSYS FLUENT*

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I. Introduction

The study of natural convection in enclosures has a wide importance in engineering applications such as solar energy systems, building insulation materials, cooling of electronic circuits, air conditioning, heat exchangers, geophysical problems and grain storage as stated by[1],[2],[3],[4]. Higher mass flow rate results in getting better mixing in room ventilation applications. The geometry investigated involves structure based on cold incline wall and isothermally heated base. The higher the temperature differences between the hot base and the cold inclined roof, the higher the velocity of the enclosed air. The hot air at the base rises towards the cold inclined roofs because of its lower density. The air rises from the hot base towards the cold incline wall forming plumes.Heat transfer through the attic space into or out of buildings is important for right-angled triangular houses in both winter and summer conditions. The attic space is usually given utmost consideration because its thermal characteristics have great influence on the conditions of the space directly below or above it.

During the design and construction of houses, it is required that the energy consume be properly minimized. Also, in some rural areas, agricultural produce is sometimes kept in the rooftops of residences either for drying or for storage. It is, therefore, desirable to have a thorough knowledge of the flow pattern and heat transfer characteristics of the attic space in realistic conditions. Natural convection in enclosed spaces has been examined in recent period in response to energy-related applications as stipulated by [5],[6],[7]

The boundary conditions for the night-time or winter-time mean the incline walls of the attic are isothermally cooled and the bottom wall is heated.The fluid flow for this type of boundary condition is mainly unstable as a result of Rayleigh Bernard instability. The instability within the attic-shaped enclosure occurs as a form of sinking and rising plumes.[8] numerically investigated laminar natural convection in a roof with an isosceles triangular cross section for wintertime conditions. The varied base angles 15^0 to 75^0, were used for Rayleigh numbers ranging from 10^3 to 10^5. Finite-volume method was used for the discretization of the governing equations. The effects of the Rayleigh number and base angle on the flow field and heat transfer were examined. It was observed that roofs having low base angles were not suitable for wintertime conditions because of high heat transfer rates from the isosceles triangular attic space of the building.In another work, [9] applied a finite volume method to study triangular enclosures for both summer and winter conditions within the range $10^3 \leq \mathrm{Ra} \leq 10^5$ for $15^0 \leq \theta \leq 75^0$. It was observed that, for winter condition, at small pitch angle, increasing Ra resulted to multicellular flow structure while, for summer condition, the temperature profile is always stable and stratified for all Ra and pitch angles. [10] examined an isosceles triangle for his experimental model and flow visualizations were carried out with heat transfer measurements for winter conditions. The velocities at some points were measure applying a laser velocimetry. The velocity measurements were carried out to help in understanding the direction and structure of the flow. The heat transfer data were obtained from temperature difference between the boundaries. It was observed that, at low Rayleigh numbers, the flow was laminar, but as the Rayleigh number was increased, the flow eventually became turbulent. It was also observed that four convective cells were present in the laminar flow regime.[11] observed that, for $10^2 \le \mathrm{Ra} \le 10^5$ considered, the flow bifurcation is time-dependent. In another study conducted by [12] on the effect of attaching baffles to reduce the heat loss through the attic during winter shows that the purpose could be achieved and also a desired temperature could be maintained in the attic.[13] investigated the occurrence of pitchfork bifurcation under winter conditions for iso-flux case. Multicellular flow patterns that were sensitive to the pitch angle were present.[10] for a right-angled triangular enclosure indicate single cell fluid circulation for Rayleigh number (Ra) up to 10^4 for values of aspect ratio (AR) between 0.02 and 1.0.The problem of natural convection inside a two dimensional triangular enclosure filled with fluid, with various aspect ratios and Rayleigh numbers ranging between 10^2 and 10^5. At low values of Ra, a single convective cell was observed for the flow structure within the enclosure and as the values of Ra increases, a multi-cellular flow structure was observed within the enclosure. An investigation to study the details of the transition from single cell to multi cell flow within the enclosure was carried out by [1]. The results of their study showed that the Aspect ratio and the Rayleigh number had a great influence on the temperature and flow structure. It was observed that as the aspect ratio decreased, the transition to multi cell flow took place at higher Rayleigh numbers. The results also showed that the primary cell will shift towards the plane of symmetry, if there is formation of secondary cell.

II. Methods / Computational details

The computational model was developed as a whole using ANSYS FLUENT as the design modeler. The CFD developed an algorithm, which solves the partial differential equation of the fluid mechanism within the enclosure. The geometry for the right-angled triangular roof enclosure was first developed and then the subdomain and boundary conditions were defined for both the laminar flow, conductive and convective heat transfer using the appropriate equations and properties. Then tetrahedral meshes were developed using a higher density at the vertices for better accuracy. Hence, about 10^5 grid elements, for elemental thick, were used for the simulation. The right-angled triangular rooftop enclosure was of air-filled (Pr=0.71) with a cross-section as shown in Fig. 1 was used. The enclosure extension in the direction perpendicular to the cross-section is assumed more than double its width so that the flow and the heat transfer are taken to be two-dimensional as stipulated by [14]. A night time boundary condition or winter condition (when isothermally cool on the inclined wall and heated on the base) was considered.

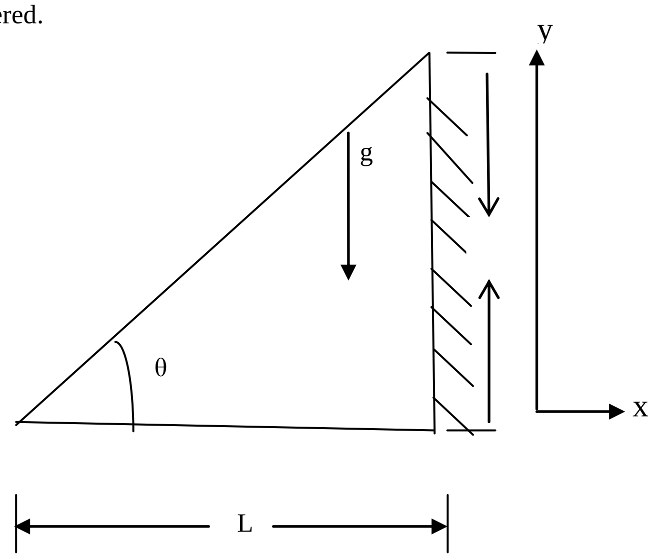

Fig. 1: Physical Model

The horizontal base depicting a ceiling for the right-angled triangular enclosure was assumed heated by the warm air from the hearth within the space below to a temperature of 4^0C, and the pitched roof was assumed covered with snow at 0^0C. Three pitch angles 18^0, 30^0,45^0 representing an aspect ratio range $0.3 \le \mathrm{AR} \le 0.9$ were simulated. This, in combination with the thermal boundary condition (winter condition) results in a range of Rayleigh number (Ra), $2.76\mathrm{x}\ 10^5 \le \mathrm{Ra} \le 8.40\mathrm{x}10^5$.

The Thermo-physical properties of the fluid in the right-angled triangular roof enclosure shown in Fig. 1 are assumed constant except the density. The Boussinesq approximation relates the variation of density with temperature of the fluid mechanism within the enclosure. With these assumptions, the governing equations for laminar natural convection flow in the right-angled triangular cavity using conservation of mass, momentum and energy.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$\frac{\partial}{\partial x}(uu)+\frac{\partial}{\partial y}(vu)=-\frac{1}{\rho}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$\frac{\partial}{\partial x}(uv)+\frac{\partial}{\partial y}(vv)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-g[1-\beta(T-T_o)]$$

$$\frac{\partial}{\partial x}(uT)+\frac{\partial}{\partial y}(vT)=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)$$

Here, x and y are the distances measured along the horizontal and vertical directions,u and v are the velocity components in the x- and y-directions, T denotes the temperature, μand $\alpha$are dynamic viscosity and thermal diffusivity, p is the pressure andρis the density; T_h and $T_c$are the temperatures at hot and cold walls, respectively; H is the height of the triangular enclosure.

The equations can be transformed into a non- dimensional form using the relations below:

$X=\frac{x}{H}$, $Y=\frac{y}{H}$, $U=\frac{uH}{\alpha}$, $V=\frac{vH}{\alpha}$, $\Theta=\frac{T-T_a}{T_H-T_a}$, $N_u=\frac{hH}{K}$, $P_r=\frac{\mu}{\rho\alpha}$,

$R_a = g\beta(T-T_a)H^3Pr/v^2$

The non-dimensional form of the governing equations:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0$$

$$\frac{\partial U^2}{\partial X}+\frac{\partial UV}{\partial Y}=-\frac{\partial P}{\partial X}+\mathrm{Pr}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)$$

$$\frac{\partial UV}{\partial X}+\frac{\partial V^2}{\partial Y}=-\frac{\partial P}{\partial Y}+\mathrm{Pr}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ra\,\mathrm{Pr}\,\theta$$

$$\frac{\partial U\theta}{\partial X}+\frac{\partial V\theta}{\partial Y}=\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right)$$

Here X and Y are dimensionless coordinates varying along the horizontal and vertical directions, respectively; U and V are the dimensionless velocity components in the X and Y-directions, respectively; θ is the dimensionless temperature; P is the dimensionless pressure; Ra and Pr are Rayleigh and Prandtl numbers, θ is pitch angle, The height of the enclosure H is taken as the characteristic length in the definition of the Nusselt Number, h is the mean heat transfer Coefficient and K is the thermal conductivity of the fluid and to ensure that the Bousinessq approximation is valid, the hot inclined roofs and cold isothermal base are varied at different temperature, for all the numerical simulations performed.

III. Results and Discussion.

Effect of Pitch Angle

The effect of the Pitch angles on the flow structure and heat transfer within the enclosure are investigated for right-angled triangular rooftop enclosure in winter condition (enclosure heated from the base walls isothermally) as shown in figure 2 (a-c). The pitch angle has great effect on the thermal characteristic, and as the pitch angle increases, the flow field within the enclosure changes.The value of the air velocity within the enclosure changes with increase in the pitch angle, and the region of the highest velocity was observed at the points where the counter rotating cells rub each other and lowest at the center of each cell formed by the convection currents and also low at the corners. The result agrees with the report of [15].

In Fig. 2(a), 18^0-pitch, the flow hits the upper inclined walls faster forming eight counter-rotating cells within the enclosure;this is as a result of the closeness between the cold inclined wall and hot base walls.Fig. 2(b), with the pitch angle increased from 18^0-pitch to 30^0, the eight counter-rotating cells that was observed in

Fig. 2(a) had reduced to three bigger cells, with one big cell occupying the right end part of the enclosure. For the 45^0-pitch enclosure, Fig. 2(c), three counter-rotating cells was also observed with one big cell occupying almost the entire enclosure. The number of the recirculating cells decreases with increase pitch angles, which agrees with the report of [16]on a right-angled triangular enclosure heated from the base wall showing that multicellular flow patterns changes with the pitch angle.

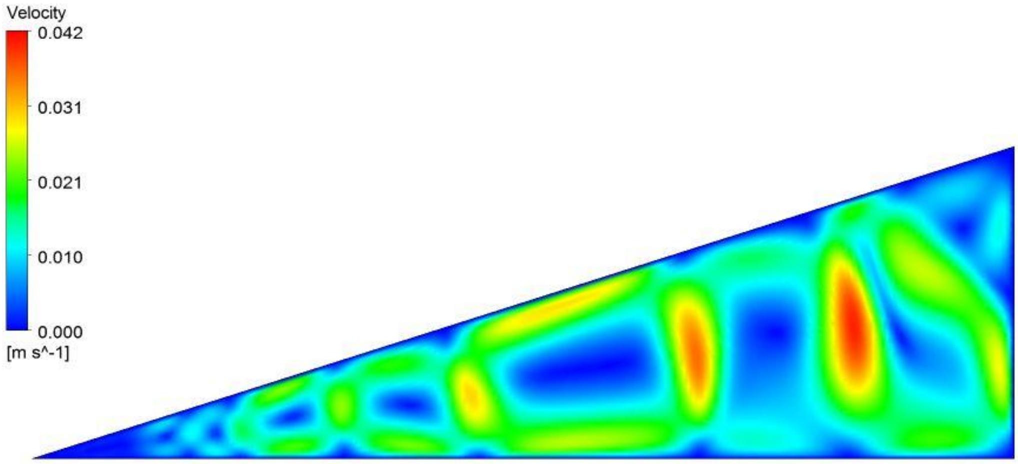

Fig. 2(a): Shows the velocity field distribution when the enclosure heated from the base walls is at (a) 18^0-pitch, $Ra=2.76x10^5$

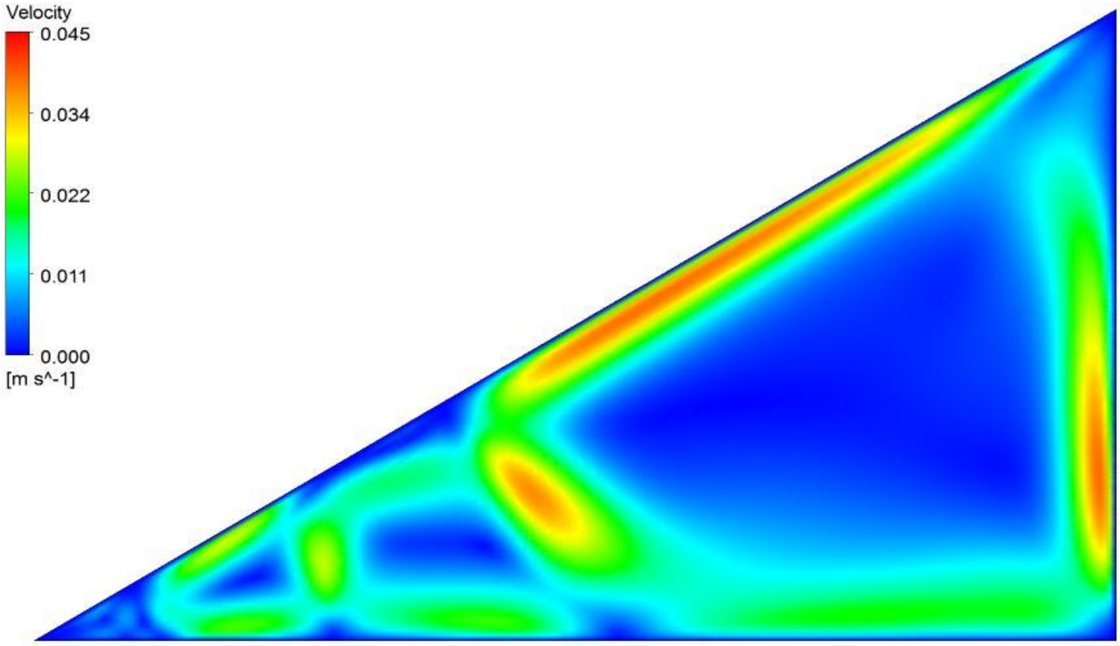

Fig. 2(b): Shows the velocity field distribution when the enclosure heated from the base walls is at 30^0-pitch,, $Ra=5.49x10^5$

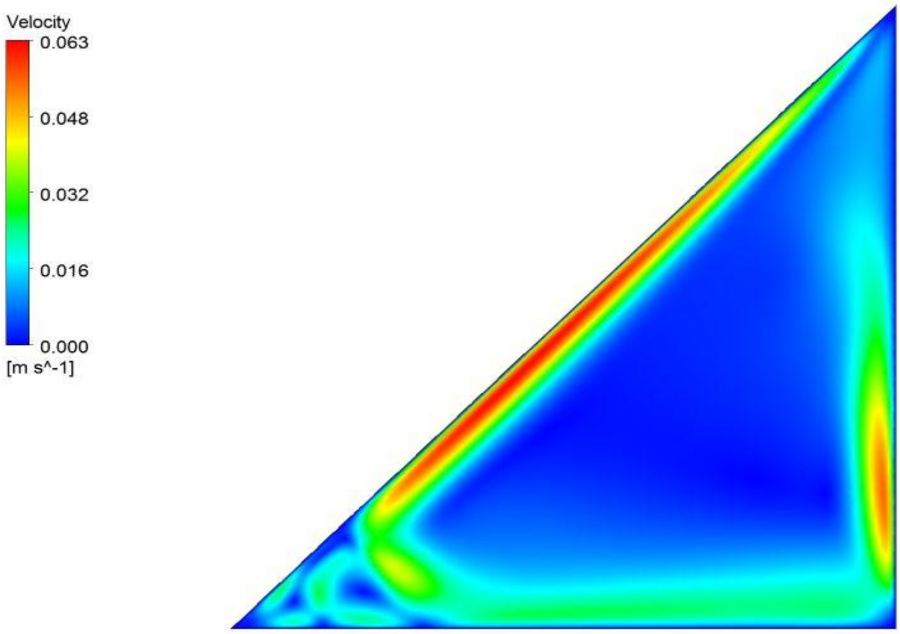

Fig. 2(c): Shows the velocity field distribution when the enclosure heated from the base walls is at 45^0-pitch,, Ra=$8.40x10^5$

Effect of Rayleigh number

The effect of the Rayleigh number on the flow structure and the heat transfer within the right-angled triangular enclosure under winter condition are investigated as shown in figure 3 (a-c). As the Rayleigh number increases, the flow field within the enclosure changes. The flow rises from the heated base in the enclosure and move towards the cold inclined roofs creating recirculating cells.In Fig. 3(a), at Ra = $2.76x10^5$ the heat transfer between the cold inclined roof and hot horizontal base walls was very high, which is as a result of the closeness between the walls. This results in eight counter rotating cells within the space. In Fig. 3(b), with increased Ra=$5.49x10^5$, three counter-rotating cells were observed with one big cell occupying the right end of the enclosure and in Fig. 3(c) for Ra=$8.40x10^5$, the cells reduced to one big cell, almost occupying the whole enclosure with two smaller cells, which shows proper mix of air within the enclosure.

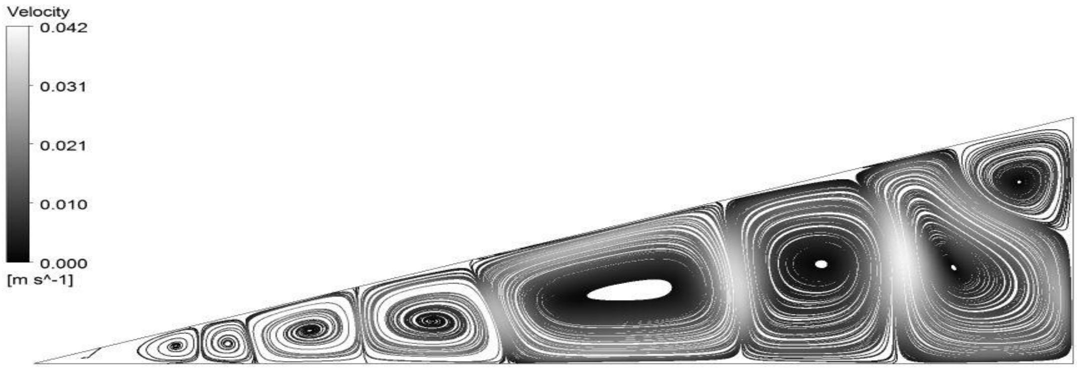

Fig. 3(a): Streamlines of the enclosure heated from below at 18^0 , Ra=$2.76x10^5$

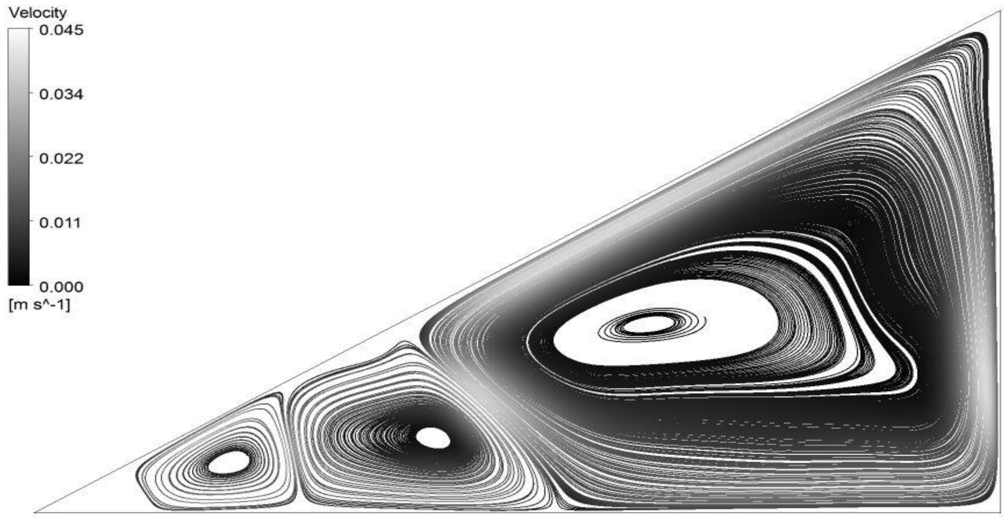

Fig. 3(b): Streamlines of the enclosure heated from below at 30^0 , Ra=5.49x10^5

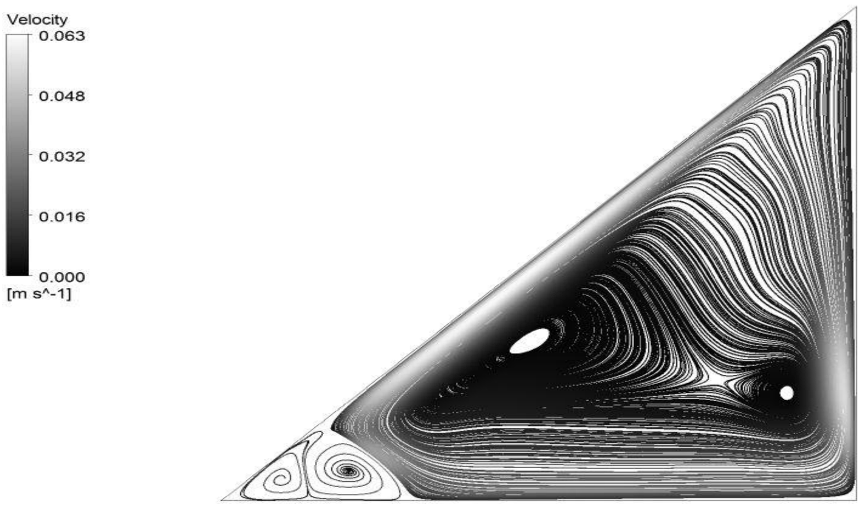

Fig. 3(c): Streamlines of the enclosure heated from below at 45^0 , Ra=8.40x10^5

This result is in agreement with the report of [5] who presented flow visualization results from experiments performed in a smoke-filled isosceles triangular enclosure heated from the base wall to show that as Rayleigh number decreases, the flow pattern became multicellular and the number of counter-rotating cells increases.

Effect of Heating Side

The effect of the heating side on the right-angled triangular enclosures was investigatedas shown in fig 4 (a-c). The inclined roofs were cooled and maintained at 273K and the base heated at temperatures 277K, giving a temperature difference of 4K. The temperature differences enable the fluids to move in the enclosure, the hot fluids at the base tend to rise towards the cold inclined roofs because of it lower density. Convection currents were noticed as the air rises from the hot base towards the cold roof forming plumes.The side at which the walls are heated is observed to have a strong influence on the temperature and flow field pattern withinthe right-angled triangular enclosures investigated

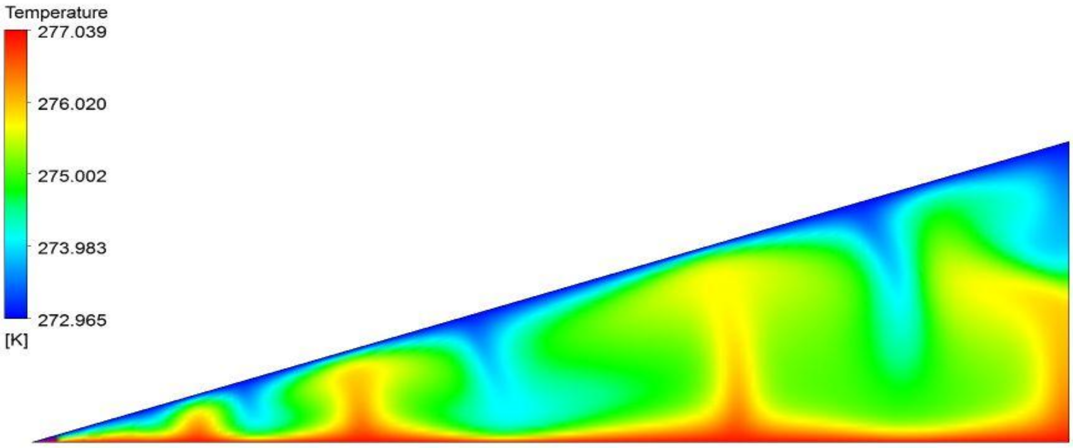

Fig. 4(a): Mean temperature distribution for pitch angle 18^0 , Ra=2.76x10^5 in winter condition (273K-277K) when enclosure was heated from the base walls isothermally

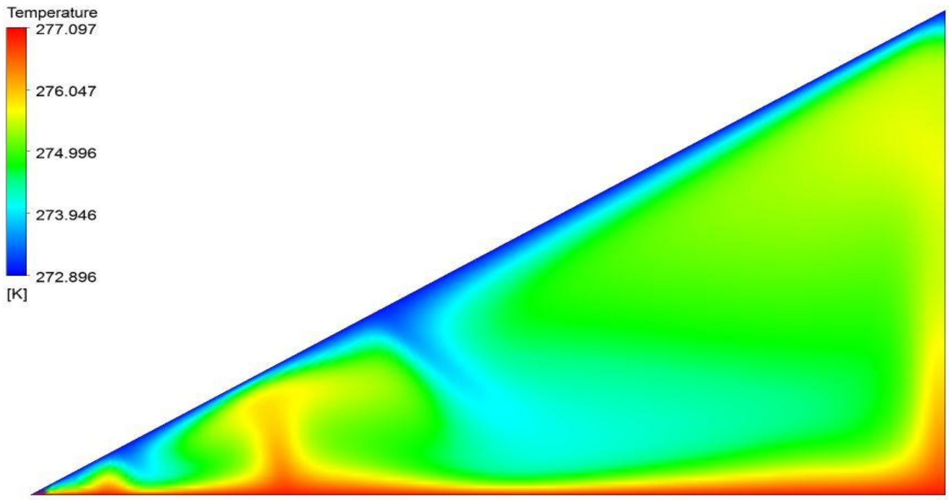

Fig. 4(b): Mean temperature distribution for pitch angle 30^0 , Ra=5.49x10^5 in winter condition (273K-277K) when enclosure was heated from the base walls isothermally

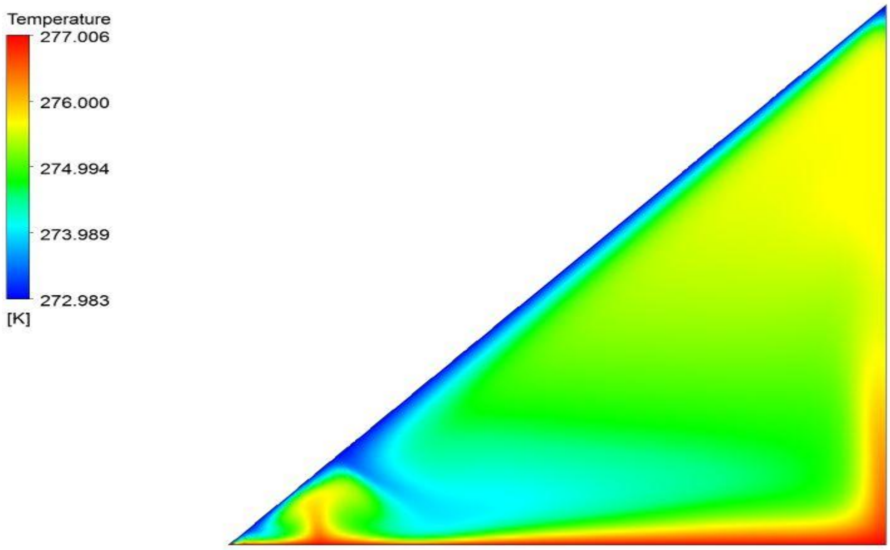

Fig. 4(c): Mean temperature distribution for pitch angle 45^0 , Ra=8.40x10^5 in winter condition (273K-277K) when enclosure was heated from the base walls isothermally

IV. Conclusion

The study of natural convection and flow simulation in right-angled triangular rooftop enclosure when heated isothermally from the base wall (winter condition) has been investigated using ANSYS FLUENT as the design modeler. The effects of Rayleigh number, pitch angle, and the heating side on the flow structure and temperature distribution within the enclosure are examined. Results show that the heat transfer between the cold inclined roof and hot horizontal base walls was very high, which was as a result of the closeness between the hot base wall and the cold inclined walls leading to multicellular flow structure with the number of cells reducing as the pitch angle increases. As the Ra increases, the number of counter-rotating cells reduces which shows proper mix of air within the enclosure.

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