The International Journal of Engineering and Science (IJES)
|| Volume || 9 || Issue || 03 || Series I || Pages || PP 55-63| 2020 ||
ISSN (e): 2319-1813 ISSN (p): 20-24-1805

Simulation of 2-D Laminar Natural Convection Heat Transfer in a Right-Angled Triangular Rooftop Enclosure using Comsol Multiphysics

Solomon Eriamiatoe[1]and kamiyo O.M[2]
Department of Mechanical Engineering
University of Port Harcourt, Rivers state, Nigeria

-ABSTRACT-

The analysis of laminar natural convection in an enclosure is as varied as the enclosure geometry, its orientation and thermal boundary conditions. In this work,simulation of 2-D laminar natural convection heat transfer in a right-angled triangular rooftop enclosure when heated isothermally from the inclined walls (summer condition) and when heated from the base wall (winter condition) are investigated using COMSOL Multiphysics code. The effects of Rayleigh number, pitch angle, and the heating side on the flow structure and temperature distribution within the enclosure are examined. Results indicate that, for winter condition, at low pitch angle, the heat transfer between the cold inclined and hot base walls is very high resulting in multicellular flow structure. But as the pitch angle increases, the number of cells reduces as small cells emerged to form bigger ones. As the Rayleigh number increases, the single cell bifurcates into more cells. In summer condition, two large counter-rotating cells are observed for the Ra and aspect range ratio considered. 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 the design and analysis of building attics and to agriculturist engage in rooftop drying or storage of agricultural produce.

KEYWORD: *Laminar Natural Convection, Pitch Angle, Right-Angled Triangular Roof Shape*

Date of Submission: 04-03-2020 Date of Acceptance: 22-03-2020

I. INTRODUCTION

The study of natural convection in rooftop enclosure is gaining importance for various engineering applications During the design and construction of a building roof, the attic space is often given paramount consideration because its thermal characteristics have great influence on the conditions of the space directly below it.Intropical climate, both humid and arid, conventional types of roof construction suffer from excessive midday overheating due to the high solar radiation incident on the surface area. Solar radiation which falls on roof is absorbed by the roof materials, making the roofing sheets to become very hot in the midday sun. A low-pitched roof, common in the tropics, is apt to trap heat in the attic. A large amount of the cooling load in residential and industrial buildings for an air conditional system is the result of heat transfer across the ceiling from the attic as stated by [1] 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 heat transfer and fluid flow in enclosed spaces has been studied extensively in recent years especially in response to energy-related applications as proposed by [2], [3] and [4]. For the enclosures heated from below (winter condition). [5] 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. [6] numerically analyzed laminar natural convection in a roof with an isosceles triangular cross section for wintertime conditions. Base angles varying from 15 degrees to 75 degrees, was 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 analyzed. 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. [7]. discovered that, for 10^2 to 10^5 values of Ra studied, the number of cells increases with increase in the Rayleigh number. Applying a finite volume method, [8] observed that, for $10^2 \leq Ra \leq 10^5$ considered, the flow bifurcation is time-dependent. In another study conducted by [9] 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. [10] examined the occurrence of pitchfork bifurcation under winter conditions for isoflux case. Multicellular flow patterns that were sensitive to the pitch angle were present.

For the case of the enclosure heated from the inclined walls (summer condition), [11] numerically investigated convection patterns in isosceles triangular enclosure using finite difference method for solving the Navier–Stokes and energy equations. Two cases of thermal boundary conditions were considered for Grashof numbers (Gr) in the range of $10^3 \leq Gr \leq 10^8$ and for various aspect ratios in the range $0.25 \leq H/B \leq 2.0$, where H/B is the aspect ratio. They observed that the maximum values of stream functions and Nusselt numbers perform damping oscillations around the steady state values. [12] observed that the thermal and flow fields remain always stable and the flow remained laminar for all cases of the Rayleigh number considered. [13] used a finite-difference representation of the steady-state stream function-vorticity-energy formulation to examine the flow structure and heat transfer rate of air in a right-triangular enclosure for Ra range of 5.6×10^2 to 4.5×10^4. They observed single cell laminar flow for all Ra. An analogous problem was simulated by [14]. They used the alternating direction implicit (ADI) numerical technique and finer grid to obtain multicellular flow patterns for Ra up to 10^6 and AR range of 0.125 to 1.0. [15] attempted comparing numerically-obtained data with previous experimental measurements for summer and winter conditions. For the summer condition, they discovered that conductive heat transfer prevails up to Ra value of 10^6 while multicellular flow patterns are obtained for the winter condition. [16] studied the effect of alternating thermal boundary conditions on the vertical and inclined walls of a right-angled triangular enclosure with the horizontal bottom adiabatic for $10^3 \leqslant Ra \leqslant 10^5$ and $0.07 \leqslant Pr \leqslant 1000$. The results show that as the Rayleigh number increases, the flow structure changes from conduction to convection dominated. [17] employed a finite volume method to study triangular enclosures for both summer and winter conditions within the range $10^3 \leq Ra \leq 10^5$ 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.The main purpose of this work is to investigate 2-D laminar natural convection heat transfer in a right-angled triangular rooftop enclosure when heated isothermally from the inclined walls (summer condition) and when heated from the base wall (winter condition) using COMSOL MULTIPHYSICS 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.

II. METHOD/APPROACH

A right-angled triangular roof enclosure 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 [18]. Two sets of boundary conditions were considered: enclosure heated from the base wall (winter condition) andenclosure heated from the inclined walls (summer condition).

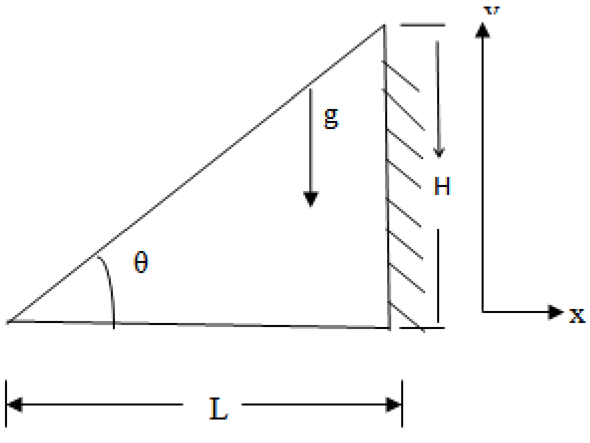

Fig. 1: Physical Model

For the winter condition, 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 23^0C, 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 $0.3 \leq AR \leq 0.9$ were simulated. This, in combination with the thermal boundary condition, results in a range of Rayleigh number (Ra), $1.28 \times 10^5 \leq Ra \leq 7.17 \times 10^6$.

For summer condition, the inclined walls represent aluminum or galvanized sheets exposed to solar radiation and heated to temperature of 30^0C, 50^0C and 70^0C. The vertical wall is an adiabatic wall and the horizontal base, depict a ceiling above an air-conditioned space, was assumed cooled isothermally and maintained at 23^0C. The computational domain coincides with the physical domain.

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, are written [19].

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

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

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

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

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.

Computational Details

The computational model was developed as a whole using the COMSOL MULTIPHYSICS Version 3.5 code. 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 10^4 grid elements, for elemental thick, were used for the simulation.

III. RESULTS AND DISCUSSION

Effect of Pitch angle

It was discovered that the pitch angle has a significant effect on the thermal characteristic of a right-angled triangular rooftop enclosure. As the pitch angle increases, the flow field within the enclosure changes. The effect of the pitch angle on the velocity field is presented in Fig. 2, when the enclosure was heated from the base walls isothermally. In Fig. 2(a), the 18^0-pitch makes the cold inclined and hot base walls to be closer, making the heat transfer between them very high. This results in multicellular flow pattern within the space. In Fig. 2(c), with the pitch angle increased to 45^0, the four counter-rotating cells observed in Fig. 2(a) and 2(b) has reduced to two but bigger cells. The bigger of the two cells occupies the mid-center of the enclosure. Also, velocity is high around the circumference of the cells but very low near the corners. The result agrees with the report of [21] on a right-angled triangular enclosure heated from the base wall showing that multicellular flow patterns changes with the aspectratio.

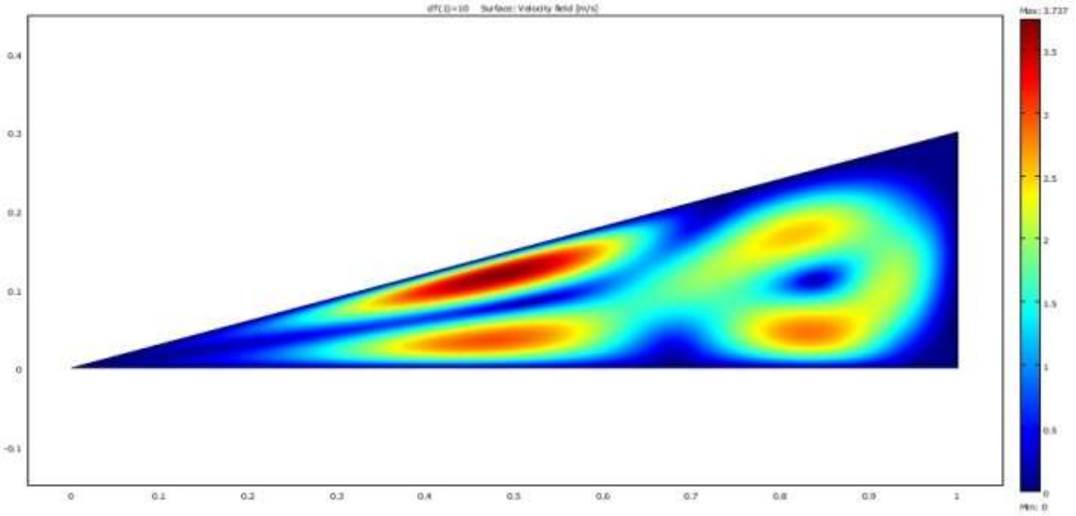

Fig 2 (a):Shows the velocity field distribution when the enclosure heated from the base walls is at a 18^{0-}Pitch,

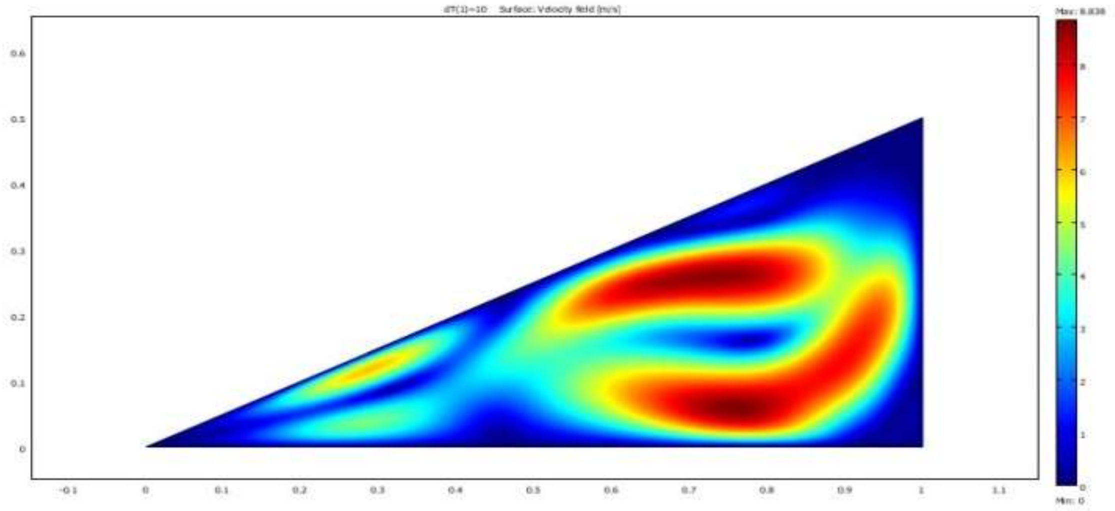

Fig 2 (b): Shows the velocity field distribution when the enclosure heated from the base walls is at a 30^{0-}Pitch,

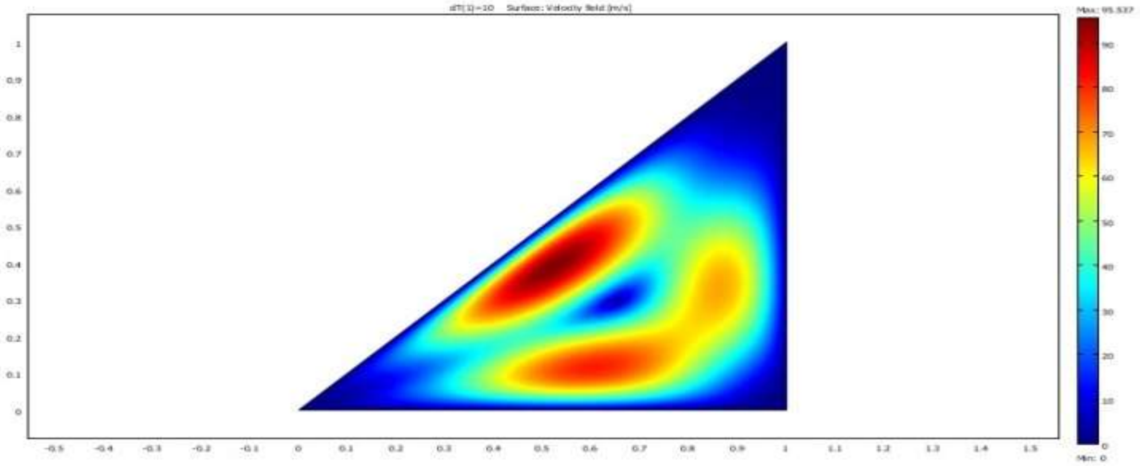

Fig. 2 (c):Showsthe velocity field distribution when the enclosure heated from the base walls is at 45^0-pitch.

Effect of Rayleigh number

A Change in Rayleigh number has a great effect on the right-angled triangular enclosure as shown in Fig. 3, for 18^0-pitch enclosure. At Ra = 1.28×10^5, a single cell fill the space. As the Ra increased to 4.43×10^5, in fig. 3(b) the elongated cell in Fig. 3(a) bifurcates into two counter rotating cells. And at higher Ra, Fig. 3(c), the cells increased to four (two big and two small cells), as the smaller cell in Fig 3(b) bifurcates. This scenario shows thorough mixing of the air within the enclosure.

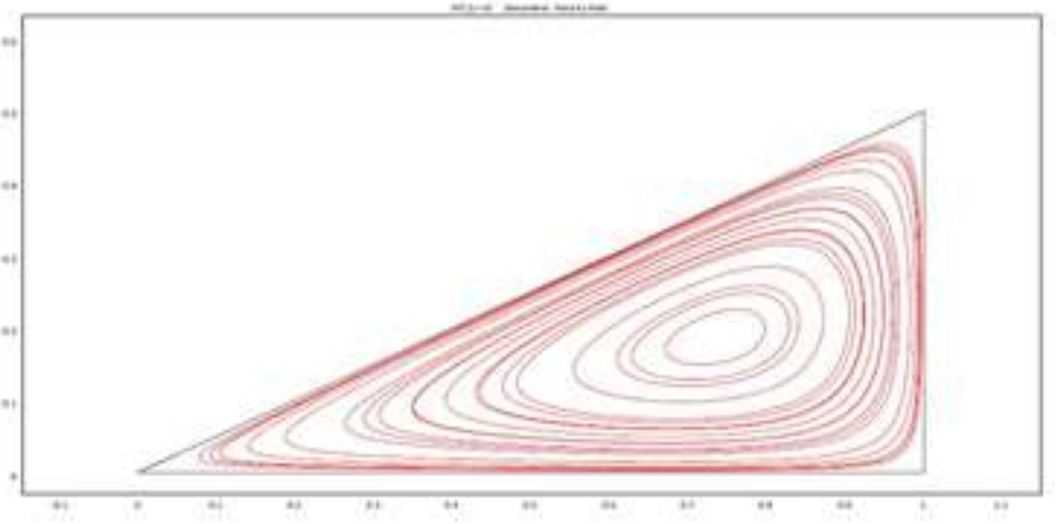

Fig. 3: (a)**:** Streamlines of the enclosure heated from below at 18^0- pitch (a) Ra=1.28 x 10^5, AR=0.3;

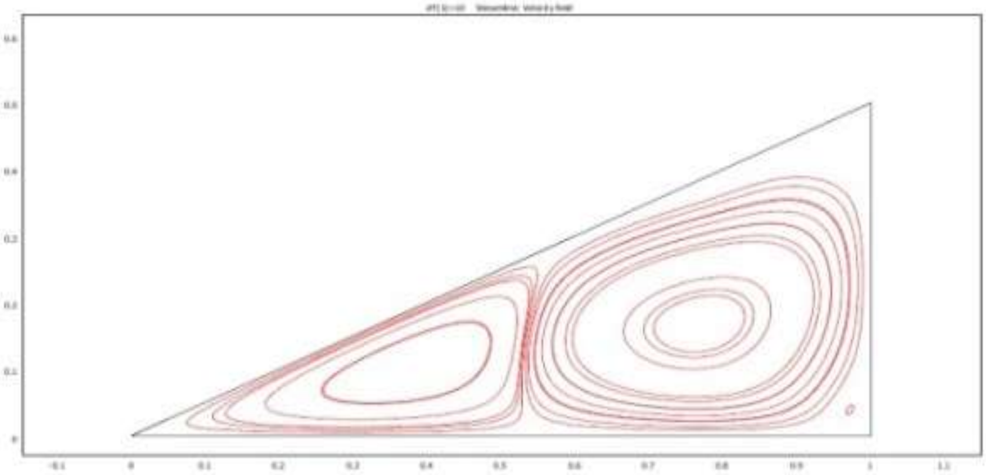

Fig. 3: (b) Streamlines of the enclosure heated from below at 18^0- Pitch, Ra=4.43 x 10^5, AR=0.3,

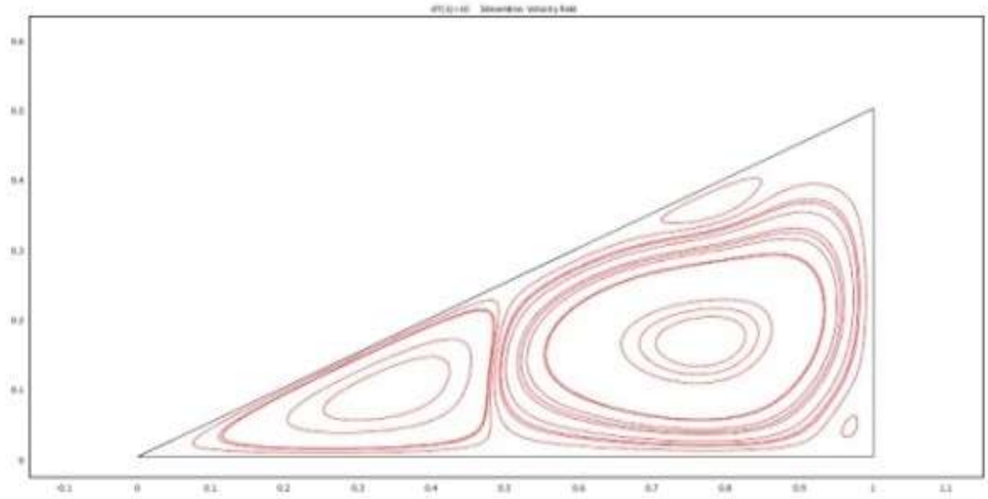

Fig. 3 (c):Streamlines of the enclosure heated from below at 18^0- Pitch,Ra =8.07 x 10^5, AR = 0.3.

This result is similar to that of [21] 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 increases, the flow pattern became multicellular and the number of counter-rotating cells increases.

Effect of Heating Side

The side at which the walls are heated is observed to have a strong influence on the temperature and flow field pattern within the right-angled triangular enclosures investigated as shown in fig. 4.

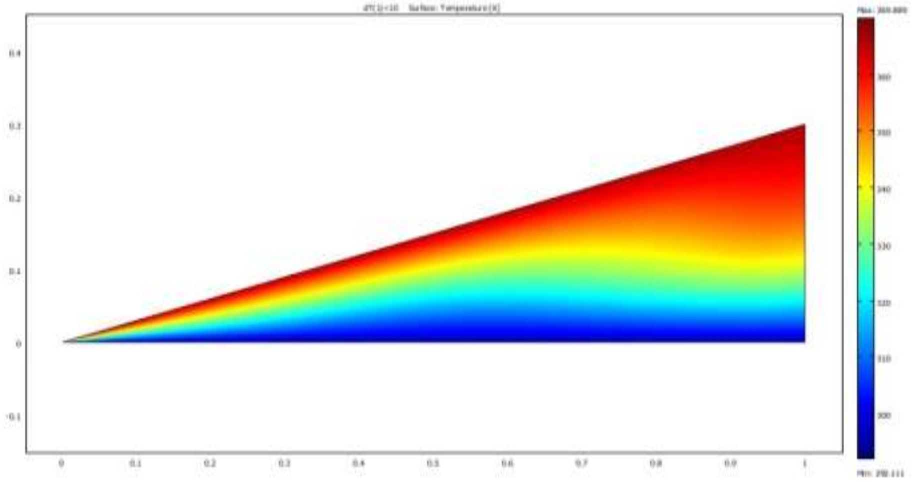

Fig. 4 (a): Mean temperature distribution when the 30^0-pitch (AR=0.45) enclosure is heated isothermally through the inclined walls Ra=1.59 x 10^6;

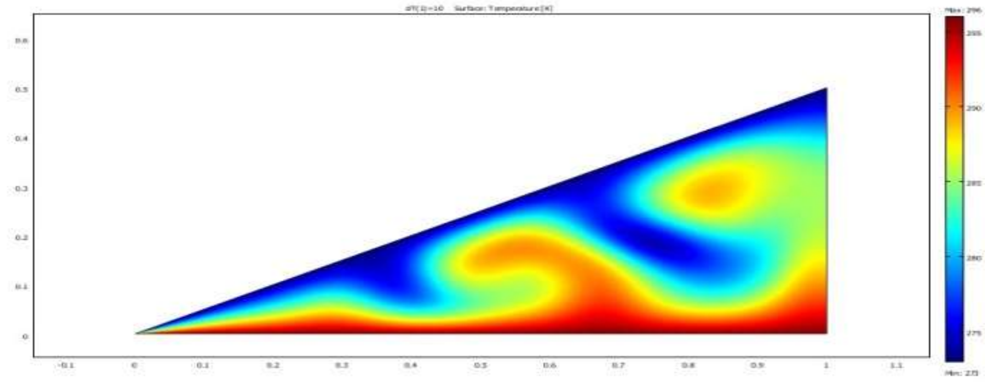

Fig. 4(b): Mean temperature distribution when the 30^0-pitch (AR=0.45) enclosure is heated (a) isothermally through the base wall, Ra=1.47 x 10^6,

When the enclosure was heated isothermally from the inclined walls, Fig. 4(a) shows the temperature is thermally stratified near the bottom corners. Hot air is found constrained to the upper part of the enclosure and movement of fluid at the mid-center is little. The results of [13], support this andin Fig. 4(b), for the enclosure heated below, the hotter air rises and a large cell having moderate temperature core was observed at the mid-center of the enclosure with the hot temperature constrained to the base.

The Practical Significance of the Study:

The practical significance of the study is to predict the positioning of heat extraction devices at high intensity areas of a right-angled triangular roof enclosure. The unwanted heat trapped within the enclosures could be effectively extracted when heat extraction device is placed at high heat intensity areas as predicted. This would help in reducing the size of the air-conditioning system required to cool the space below, minimize the use of thermal insulation across the ceiling, and extends the period of thermal comfort within the space without reliance on mechanical air-conditioning thereby reducing the annual energy cost. The work is, also, expected to be very useful to agriculturists engaging in rooftop drying of agricultural produce and also to professionals engage in the design and construction of buildings.

IV. CONCLUSION

The simulation of 2-D laminar natural convection heat transfer in a right-angled triangular rooftop enclosure using COMSOL Multiphysics as the design modeler has been investigated for both summer and winter conditions. For the winter condition, results show that the high heat transfer between the hot base wall and the cold inclined walls led 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 increases. For the summer condition, there were two counter-rotating cells within the enclosure for all the Rayleigh number investigated.

REFERENCES

[1]. American Society of Heating, Refrigerating and Air-conditioning Engineers, (2005)" ASHRAEHandbook: Fundamentals", SI Edition, ASHRAE Inc., USA.

[2]. Oztop, H.F., Varol, Y., Pop, I., (2009) "Investigation of natural convection in triangular enclosure filled with porous media saturated with water near 4^0C" Energy Conversion Management, Vol. 50, pp. 1473–1480.

[3]. Varol, Y., Oztop, H.F. and Varol, A., (2006) "Free convection in porous media filled right-angle triangular enclosures" Int. Comm. Heat Mass Transfer, Vol. 33, pp. 1190-1197

[4]. Kent, E.F. (2009) "Numerical analysis of laminar natural convection in isosceles triangular enclosures for cold base and hot inclined walls" Mechanics Research Communications, Vol. 36, pp. 497–508.

[5]. Bejan, A. and Poulikakos, D., (1982) "Natural convection in an attic shaped space filled with porous material" Journal Heat Transfer, Vol. 104, pp. 241-247

[6]. Kent, EF., (2010) "Laminar Natural Convection in Isosceles Triangular Roofs in WintertimeConditions," Heat and Mass Transfer, Vol. 31 pp. 1068-1081

[7]. Hasani, S.M.F., Chung, B.T.F., (1997) "Laminar Natural Convection in a Triangular Enclosure", Proc. ASME Ocean Engineering Division, D.T. Valentine, and C.C. Jahnke, (eds.), pp.107-116

[8]. Ridouane, E. H., Campo, A., (2006) "Time-depending Pitchfork Bifurcation in the Thermal Convection Flow Confined to an Isosceles Triangular Cavity Heated from Below", Proceedings of the 9th AIAA/ASME Joint Thermophysics Heat Transfer Conference, California.

[9]. Ridouane, E. H., Campo, A., (2007) "Effects of Attaching Baffles onto the Inclined Walls of Attic Frames for Purposes of Energy Conservation", Heat Transfer Engineering, Vol.28, No.2, pp.103-111
[10]. Omri, A., Najjari, M., Nasrallah, S.B., (2007) "Numerical Analysis of Natural Buoyancy-Induced Regimes in Isosceles Triangular Cavities", Numerical Heat Transfer: Part A, Vol.52, No.7, pp.661-678.
[11]. Karyakin, YU.E., Sokovishin, YU.A., (1988) "Transient natural convection in triangular enclosures", International Journal of Heat and Mass Transfer, Vol. 31, pp. 1759–1766.
[12]. Flack, R. D., (1980) "The Experimental Measurement of Natural Convection Heat Transfer inTriangular Enclosures Heated or Cooled from Below", J. Heat Transfer, Vol.102, pp.770 -772.
[13]. Akinsete, V.A., Coleman, T.A., (1982) "Heat Transfer by Steady Laminar Free Convection in Triangular Enclosures," Int. J. of Heat and Mass Transfer, Vol. 25, No.7, pp.991-998
[14]. Asan, H., Namli, L., (2000) "Laminar Natural Convection in a Pitched Roof of Triangular Cross- Section: Summer Day Boundary Conditions", J. Energy & Buildings Vol.33, pp.69-73.
[15]. Ridouane, E. H., Campo, A., McGarry, M., (2005) "Numerical Computation of Buoyant Airflows Confined to Attic Spaces under Opposing Hot and Cold Wall Conditions", Int. J. Thermal Sciences, Vol.44, pp.944–952
[16]. Basak, T., Roy, S., Thirumalesha, C., (2007) "Finite Element Analysis of Steady Natural Convection in Triangular Enclosure: Effects of Various Thermal Boundary Conditions", Chemical Engineering Science, Vol.62, No.9, pp.2623-2640.
[17]. Kent, E.F., (2009) "Numerical Analysis of Laminar Natural Convection in Isosceles Triangular Enclosures", Proceedings of the Institution of Mechanical Engineers Part C: Journal of Mechanical Engineering Science Vol.223, No.5, pp.1157-1169.
[18]. Penot, F., N'Dame, A., (1992) "Successive Bifurcations of Natural Convection in a Vertical Enclosure Heated from the Side", Heat Transfer: Proc. 3rd UK National Conference and First European Conference on Thermal Sciences, Birmingham, UK, Vol. I, pp. 507-513.
[19]. Comsol, A.B., (2010) "User's Guide",COMSOL MULTIPHYSICS Version 3.5.
[20]. Salmun, H., (1995) "Convection Patterns in a Triangular Domain", Int. J. Heat Mass Transfer, Vol.38, No2, pp.351–362
[21]. Holtzman, G. A., Hill, R. W., Ball, K.S., (2000) "Laminar Natural Convection in Isosceles Triangular Enclosures Heated from Below and Symmetrically Cooled from Above", J. Heat Transfer, Vol.122, No.3, pp.485–491.

Solomon Eriamiatoe, Et.Al "Simulation of 2-D Laminar Natural Convection Heat Transfer in a Right-Angled Triangular Rooftop Enclosure using Comsol Multiphysics" *The International Journal of Engineering and Science (IJES)*, 9(03) (2020): 55-63.