70(10A): 199-205; 2022. DOI: 10.18311/jmmf/2022/31225

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: www.informaticsjournals.com/index.php/jmmf

A Numerical Investigation of Natural Convection in a Porous Enclosure with Lower Wall Heating

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Abstract

Fluid movement and heat transmission study of consistent and non-consistent heated porous material has emerged as a discrete study field in the last thirty years, owing to its relevance in abundant applications, including waste used in nuclear power plant and fibres insulations, solar collectors, solar Fresnel and so on. In recent decades, there has been a surge in interest in studying various elements of the porous media. This enormous level of attention has resulted in a slew of research publications addressing a wide variety of issues affecting porous materials, including understanding their structure, deformation, and buoyant heat transfer, to name a few. The investigate of the porous material is one of the classical topics in the field of science. In this research project, free convection is inspected and evaluated on a trapezoidal porous enclosure with analysing dissimilar Rayleigh numbers ($10^1 \leq Ra \leq 10^3$) we get efficient results in Rayleigh number 10^3, so for our further research on this paper we keep Rayleigh as constant (i.e., $Ra = 10^3$) and aspect ratios ($0.25 \leq H/L \leq 1$). The effect of Ra and AR on temperature contours, Nusselt numbers pf both mean and local has been analysed and presented. This provided a result in which the mean Nu increased by increasing the H/L ratio and Modified Ra. In addition, convection mode is dominant when Rayleigh number is high. The outcome results are differentiated with those found in the literature and were found to be in good accordance.

Keywords: *Trapezoidal cavity, buoyant heat transfer, aspect ratio, and Nusselt number.*

1.0 Introduction

A porous medium is frequently made up of a solid matrix that has been bonded together to form a network similar to web-like. The network like this medium is set up in just like a way that pores from between the solids. These small voids i.e., pores regulate the flow of liquid across the permeable substance. Small void (Pore) size is an important factor in describing the physicality of porous media. The relative size of the solid region and the area filled by pores is expressed by porosity, which is defined as the ratio of volume filled by pores to the overall volume of the medium. The permeability of natural porous media is often less than point six (0.6). There is a variety of porous materials that can be found in nature and those that can be manufactured artificially. Wood, coal, limestone, sand, and homo sapiens body parts are examples of permeable media that naturally exist. Artificial porous media include concrete, fibreglass, and fabric. Solid matrix structure, solid matrix deformation, and other areas of porosity-related study are all crucial. One such critical component is investigating heat and fluid movement behaviour within the material. The liquid flow can also be in either one-phase or many phase. In this research, it can be done on 2 discrete scales: microscopic and macroscopic. The

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microscopic inquiry is focused on solid matrix size or void (pore) size, whereas in macroscopic investigation it is focused on attributes assessed over a normal mean volume. This work aims to use a macroscopic technique to investigate heat and fluid transport inside porous materials.

A pioneer in this subject, Henry Darcy, published the Darcy law, a formula for estimating the flow properties of porous media, in 1856. While researching the hydrologic system of Dijon, France, he came up with this law. His law was used to investigate flow in the porous medium. His law is still frequently used in general, with many researchers using it to anticipate liquid behaviour in the porous material. In Darcy studies the water filtration circumstance, but his physical explanation was limited. Dupuit was the one who later explained it physically using theoretical ideas. In addition to Darcy, several researchers have made significant contributions. By introducing a new term that accounted for flow resistance, Forchheimer altered the Darcy equation. Brinkman looked at the impact of viscous shear stresses caused by a porous media surface near the fluid. Recent research has employed these 3 models, or amalgamations of these models, to account for movement behaviour in various contexts.

Because of its increasing importance, many researchers have investigated porous matrix by varying geometry. In their research A.B. Irfan et al. [1] investigated radiation and free convection effect in a cylindrical body with permeable matrix. They used finite element method (FEM) to solve the controlling equations. From this study it is observed that the average Nusselt number rises substantially with increase in radiation factor. Also, when aspect ratio is approximately one, Nusselt number has the highest value and reducing the radius ratio decreases the Nusselt number.

Heat transfer in a random shaped cavity containing porous matrix was studied by Irfan Anjum Badruddin [2]. He changed the height and breadth of the energy source to study its effect on heat transmission properties. He used finite element method (FEM) to solve the controlling equations. From this study it is seen that momentum of heat transmission in porous medium is affected by boundary conditions. Wiratchada et al. [3] conducted a quantitative study on free convection in square porous enclosure with discrete heat source. They varied the position of discrete heat source. They differed the Darcy number from 10^{-4} –10^{-2} while Rayleigh and Prandtl number are assumed to be constant. They used finite element method (FEM) to solve the controlling equations. Outcomes were presented in the form of isotherms, streamlines, heat lines and it can be observed that the temperature is equally distributed in the cavity.

F.L. Bello-Ochende [4] studied the pattern of energy distribution through free convection in square enclosure when energy source is varied vertically. The heat line patterns for increase in Rayleigh number were presented. Centro symmetric characteristics about the vertical mid-section were observed for Rayleigh Numbers post the critical value. TanmayBasak et al. [5] studied free convection in square enclosure with porous matrix. They used Penalty finite element method for the study. The temperature of the perpendicular wall was constant and top wall was insulated while the bottom wall temperature was changed uniformly and non-uniformly. The performance of their numerical procedure was constant for both continuous and discontinuous boundary conditions for a range of 10^3 to 10^6, 10^{-5} to 10^{-3} and 0.71 to 10. From this study it is noted that for all Rayleigh numbers, rate of heat transmission at centre of the base wall of cavity is maximum non-uniform heating condition than steady heating condition.

Yasin Varol et al.[6] investigated free convection (steady state) in right angle triangle cavity.They assumed that the inclined vertical walls are insulated while the bottom walls temperature is changed uneqally. They used finite element method [FEM] to solve the controlling equations.They varied the aspect ratio between 0.25 to 1.0 and Rayleigh numbers in range of 50 to 1000 for the study. From this study we can observe that decrease in aspect ratio leads to growth in rate of heat transfer.

Dr. Falah A. Abood [7] studied free convection in square enclosure with unity aspect ratio and a trapezoidal (right-angled) cavity with 0.45 and 0.25 aspect ratio values. He cooled the vertical walls, sinusoidally heated the bottom wall ($0.5(1-\cos(2\pi x))$), while other boundaries were adiabatic. He used FEM (i.e., finite element method) to solve the controlling formula. The research was carried out in a Rayleigh number range of 100 to 1000. From this study we can observe that heat transfer coefficient will increase if we increase the aspect ratio and value of Rayleigh number.

K. Aparna et al. [8] studied free natural convection in trapezoidal shape cavity with porous matrix. The lower wall temperature was changed uniformly and non-uniformly, top wall was cooled, and side boundaries were adiabatic. They used finite element method [FEM] for solving the controlling equations. They carried out the study for Rayleigh number values of 100 to 2000 while aspect ratio had a value of 0.5. From this study it is seen that the value of Nusselt number is maximum when the bottom wall is heated uniformly when compared to linearly and sinusoidally varying conditions.

Nawaf Saeid et al. [9] investigated natural convection in square porous enclosure. They assumed the vertical walls temperatures to be changed unequally. Also, a discrete heater is assumed to be attached on one of the vertical walls while other boundaries are at a continuous temperature condition. The parallel horizontal walls ware assumed to be adiabatic. They used finite element method to solve the controlling equations. The investigation was carried out for discrete positions of heater along the vertical wall in a Rayleigh number range of 10 to 1000. From this study we can observe that position of heater affected heat transfer. Seetharamu. K. N et al. [10] investigated free convection in trapezoidal enclosure with porous medium while maintaining a constant aspect ratio. The left wall was heated and another wall was cooled. The other walls were assumed to be adiabatic. The investigation was carried out in a Rayleigh number range of 10 to 1000 while maintaining a constant aspect ratio value of 0.5. From this study it is seen that Nusselt number has a maximum value in the right wall which has constant temperature when compared to the other wall which is changed linearly. This leads to increase heat transfer rate.

2.0 Governing Equations

Numerous presumptions are used to derive the controlling equations. The Presumption are: Constant porous media and fluid characteristics, impenetrable cavity boundaries, using Boussinesq approximation to computation of inertia and density while assuming viscous drag terms is relatively small in the momentum equation so it is negligible. Governing equations based on these presumptions are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad \text{... (1)}$$

Darcy formula (momentum equation)

$$u=\frac{-K}{\mu}\frac{\partial p}{\partial x} \quad \text{... (2)}$$

Darcy's law velocity in the horizontal direction can be used to explain the velocity in the x-direction.

$$u=\frac{-K}{\mu}\frac{\partial p}{\partial x} \quad \text{... (3)}$$

Velocity in x-direction is shown below,

$$v=\frac{-K}{\mu}\left(\frac{\partial p}{\partial y}+\rho g\right) \quad \text{... (4)}$$

The permeability K of permeable medium can be expressed as

$$K=\frac{D_P^2\phi^3}{180(1-\phi)^2} \quad \text{... (5)}$$

The Boussinesq approximation as

$$\rho=\rho_\infty[1-\beta_T(T-T\infty) \quad \text{... (6)}$$

Momentum equation

$$\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}=\frac{Kg\,\beta_T}{\gamma}\frac{\partial T}{\partial x} \quad \text{... (7)}$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad \text{... (8)}$$

Revised Rayleigh (Ra) number

$$Ra=\frac{g\beta_T\nabla TKL}{\nu\alpha} \quad \text{... (9)}$$

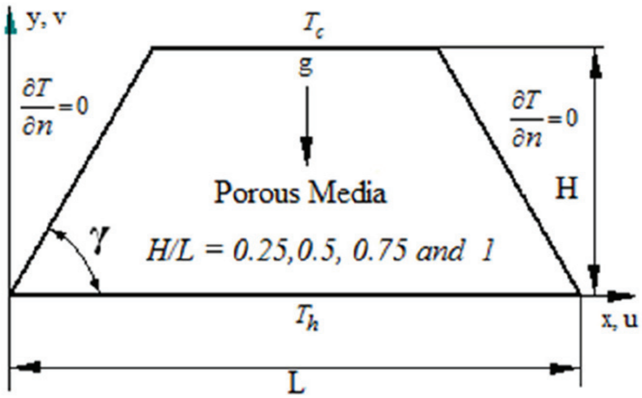

Figure 1: Physical Domain

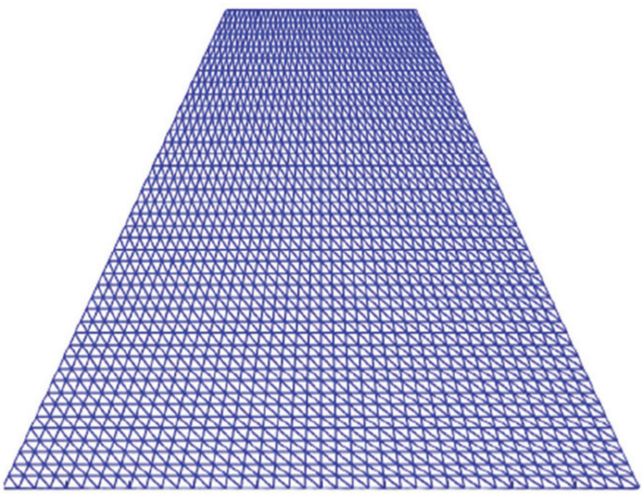

Figure 2: Triangular Mesh for porous cavity

Table 1: Grid convergence at Rayleigh number (Ra) = 1000

Grid independence Test	
Grid Dimension	Nu
11 × 11	5.4343
21 × 21	6.5783
31 × 31	7.5999
41 × 41	8.2356
51 × 51	8.2358
61 × 61	8.2361

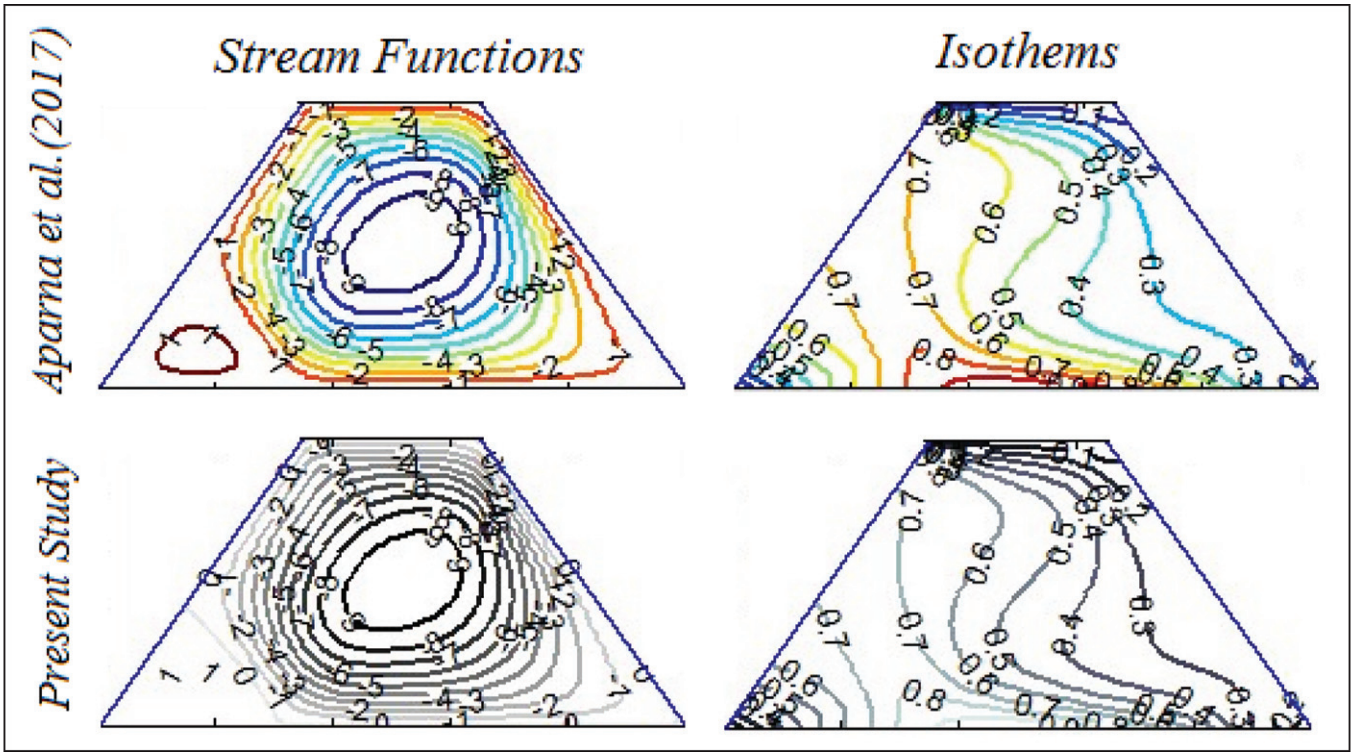

Figure 3: Comparing K. Aparna and present study of streamlines and Isotherms with same boundary condition as K. Aparna madam paper

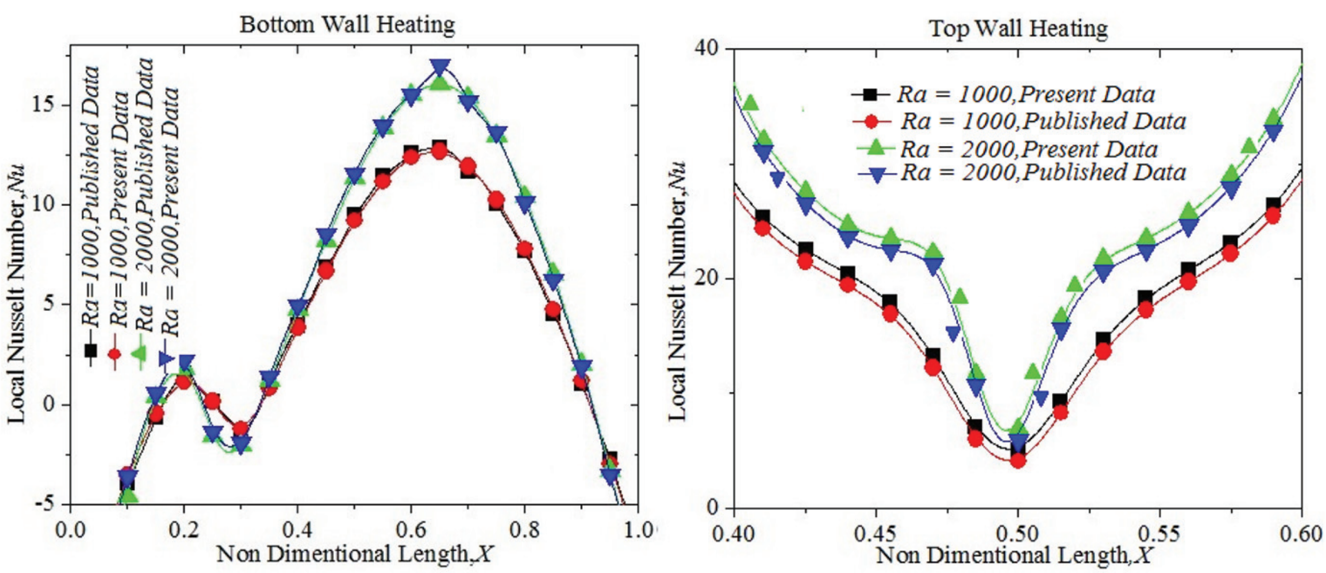

Figure 4: Comparing K. Aparna results with our present studies of Local Nusselt Number

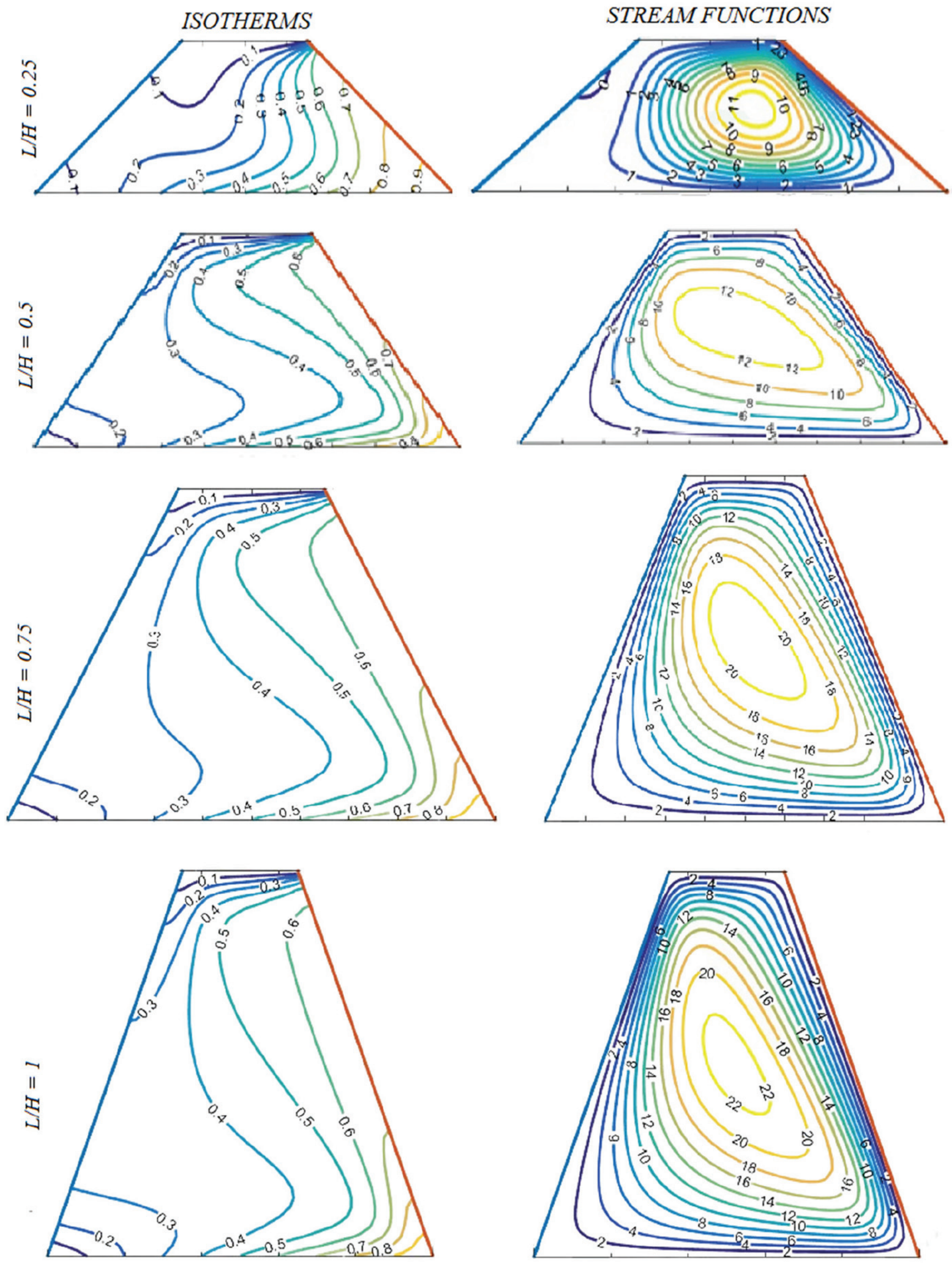

Figure 5: Streamlines and Isotherms of lowerborder Linearheating with Different aspect ratio for Ra=1000

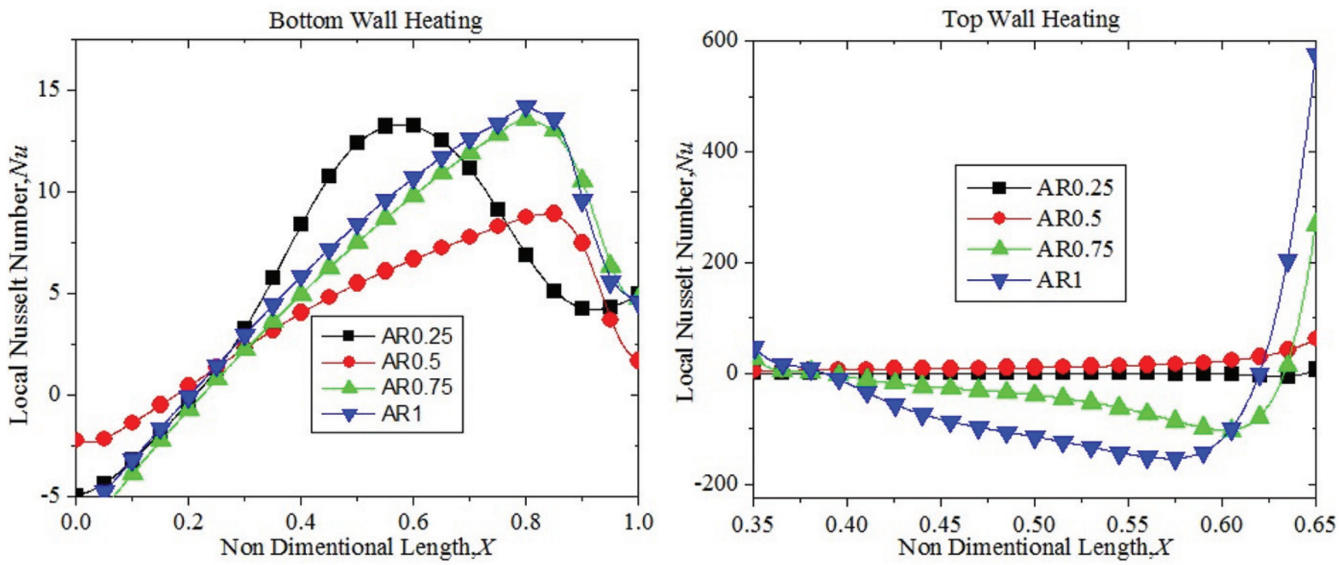

Figure 6: Variation of Local *Nu* with respect to Aspect ratio *AR*

Using FEM, controlling solutions are obtained. The numerical calculations are on free natural buoyancy heat removal in a trapezoidal enclosure are selected to demonstrate the anticipatory compatibility and accuracy of the current methodology. The physical realm of this study has a 55^0 degree angled adiabatic surface.

For the study, different grids with dimensions ranging from 1111 to 21×21 to 31×31 to 51×51 and 61×61 are employed. The overall rates of heat transmission for the described cavity structure are listed in Table 2. It should be observed that the value for a grid size of 21×21 is 6.5783 and that it rises as the grid becomes more precise and maintains at a value for grid sizes13 of 41×41. Additionally, this number nearly holds true for the following sizes 51×51 and 61×61. Due to this, further calculations are performed using a grid of 41×41.

Code Validation

Code validation method is replicated from K Aparna et al [8]. The comparison between their study and the present study is show in Figures 3 and 4.

Plots on the left of Figure 3 in the domain represent streamlines, and plots on the right represent isotherms. Figure 4 compares these two studies' measurements of the Nusselt number at the heated wall. The findings of the K Aparna et al. study and the current investigation are very similar. This graph serves as evidence that our code is valid.

3.0 Results and Discussion

Due to the linear heating and cooling of the top wall, the liquid begins to rise from the lower corner to the angled wall and flow bottom along the continuously chilled right vertical border. The result was as anticipated, as depicted in Figure 5. The absence of radiation's influence lessened the fluid flow's intensity and caused it to be deflected downward. As it approaches the cold boundary's corner, fluid rises. When the low-temperature liquid reaches the hot wall after emerging from the hard border, it first rotates in a clockwise direction. At $Ra=10^3$, conduction is the predominant heat transfer route, and the flow field values are minimal. With regard to the horizontal and vertical symmetry lines, the flow fields have an oval form when Ra is high, with higher values in the inner one and stationary ($\psi = 4$) at the core. The lower portion of the hollow has no radiation. Hence the core is deformed horizontally.

Figure 6 shows variation of average Nu with and without radiation inside the trapezoidal porous cavity for a given value of *Ra*=1000. With the effect of AR, the local Nusselt numbers increase sharply at the higher values of *Ra*. The mean *Nu* rises with a rise in aspect ratio parameter (AR = 0.25,0.5, 0.75 and 1).

4.0 Conclusion

The primary analysis of the current paper is about the effect of constant Rayleigh number with different aspect ratio on convection method within a permeable trapezoidal cavity. It is possible to distinguish between the outcomes in Figure 5, which exhibit difference in isotherms and streamlines with changes in aspect ratios. It has been investigated how natural convection occurs in a trapezoidal enclosure with a linear temperature profile on one bottom wall. Using the FDM, the governing equations and boundary conditions are resolved (finite difference method). The following inferences have been noted from the current computations –

- For constant Rayleigh numbers, conduction across the fluid layers dominates heat transfer.
- Convection is dominated by an increase in Rayleigh. For every Ra taken into account, convection is the primary mode of heat transmission in tall enclosures (AR = 1).
- The Nusselt number is rising as AR increases with high-value Ra.
- As different aspect ratios are increased, the Nusselt grows.
- For low AR (AR 0.5), the trapezoidal enclosure significantly impacts the local Nusselt. However, with higher AR (AR=1), local Nusselt remains unchanged.
- The mean Nu rises in bottom wall than in top wall.
- The convection dominance mode is observed up to Ra d" 1000.
- The mean Nusselt is higher with convection (AR=1)

5.0 References

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