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Natural Convection Flow and Heat Transfer in an Enclosure Containing Staggered Arrangement of Blockages

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Abstract

The work reported in this paper is a numerical study of airflow and heat transfer for low turbulence buoyancy-driven flow in a rectangular cavity partially filled with solid objects. The two vertical walls were maintained at constant temperatures giving a temperature differential of 42.2 °C resulting in a characteristic Rayleigh number of 1.45×109. Two different types of blockage arrangements were considered for analysis, and these consist of In-line and Staggered arrangements of 12×6 and 12×3 objects. In all cases, steady state flow and wall heat transfer data at the mid-height and mid-width of the cavity are presented. The flow domain displayed a stable core region and the average core temperature was found to be strongly influenced by different stacking arrangement of solid objects. In general, the staggered arrangement resulted in lower heat transfer through the surfaces which is linked with the suppression of turbulence within the boundary layers close to the surfaces.

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Keywords: Low turbulenc, Natural convection, Heat transfer, CFD, Product stacking and arrangement

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1. Introduction

Buoyancy driven heat transfer inside cavities has been the subject of extensive research for the last two decades due to the growing demand for detailed quantitative knowledge of the transfer processes and also due to its relevance in many practical applications [1, 2]. The basic set up for such flows, which has also attracted most attention from researchers, is a rectangular cavity filled with dry air whose opposing vertical walls are heated differentially [3-6]. In the case of a rectangular cavity of height H, the natural convection heat transfer from hot to cold walls is characterized by the formation of a slow moving vortex. This vortical motion is often interpreted as an ‘engine’

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which transfers heat from the heated surface (source) to the cold surface (sink). The intensity of flow is conveniently expressed by the Rayleigh number, $Ra = g\beta\Delta TH^3/\alpha\nu$, where, H is the height of the cavity, β is coefficient of thermal expansion, ΔT is the temperature difference between the vertical walls and α and ν are the thermal and molecular diffusivities of the fluid respectively. Depending on the Rayleigh number the flow can be categorized as turbulent or laminar [7-9]. Rayleigh numbers less than 10^8 indicate a buoyancy-induced laminar flow, with transition to turbulence occurring over the range of $10^8 < Ra < 10^{10}$ [10].

Another trend in buoyancy driven flow research has been focused on the examination of enclosures partially filled with solid products [2, 11]. The flows in such confined spaces develop as a result of temperature gradient which is further complicated by the interactive effects of solid products on the airflow and heat transfer. This interest has grown due to the relevance in the design of a wide range of practical applications such as thermal management of indoor environments, cooling of electronic panels, thermal management of agricultural blockages, stacking of items in cold storage etc. Unlike porous media, these obstacles are not in contact with each other but are close enough to influence the transfer processes significantly. The majority of studies in this category are concentrated on steady state laminar flow of Rayleigh number over the range 10^4 to 10^8 [12] investigating the flow induced by temperature gradient. Typical examples of studies in this category are the works by Das and Reddy [13], Desrayaud and Lauriat [12], and Yoon et al. [14], all of which are limited to steady state two dimensional laminar natural convection flow of Rayleigh number ranging from 10^5 to 10^8.

Work has been done for empty box and box full of isolated solid products but none has been reported for isolated solid products arranged in clusters in different parts of the chamber. This may be relevant for storage, design and determining the optimum location of clustered heating elements. The aim of this paper is to explore the heat transfer and flow field inside a rectangular cavity for different arrangements and stacking of these solid blockages and, in particular, to address the influences of in-line and staggered arrangement on the heat transfer, airflow and turbulence quantities. To achieve the above aims, a systematic two-dimensional numerical investigation of low turbulence natural convection flow and heat transfer in a rectangular confined space containing such isolated solid cylindrical objects has been conducted.

Nomenclature

H	height of the cavity (m)
L	width of the cavity (m)
x, y	displacement in x and y direction
Nu_{local}	local Nusselt number, (= hL/k)
Ra	Rayleigh number, $(= (g\beta\Delta TH^3)/\nu\alpha)$
y^+	non-dimensional wall distance
LR *k-ε*	Low Reynolds number turbulence model

2. Flow Domain

In this study, particular emphasis is placed on quantifying the airflow, turbulence quantities and heat transfer due to various arrangements of solid objects. The geometrical configurations used in these investigations are shown in Fig.1 for 12×6 blockages and are similar to the cavities used in previous investigations [15-17]. As can be seen, the objects are stacked as in-line and staggered. The rectangular cavity has an internal dimension of height, H = 1000 mm and width, L = 500 mm and the cylindrical objects are of diameter 40mm. For this arrangement, the volume occupied by the solid objects is about 18.1% of the total cavity.

Another set of stacking was considered by choosing 12×3 objects for three different cases of staggered arrangement as shown in Figs.2. These are identified as Case 1, Case 2 and Case 3. Exactly similar cases were considered for in-line stacking and an example of Case 3 is shown in Fig. 2. The volume occupied by blockages for 12×3 arrangements represents about 9% of enclosure volume.

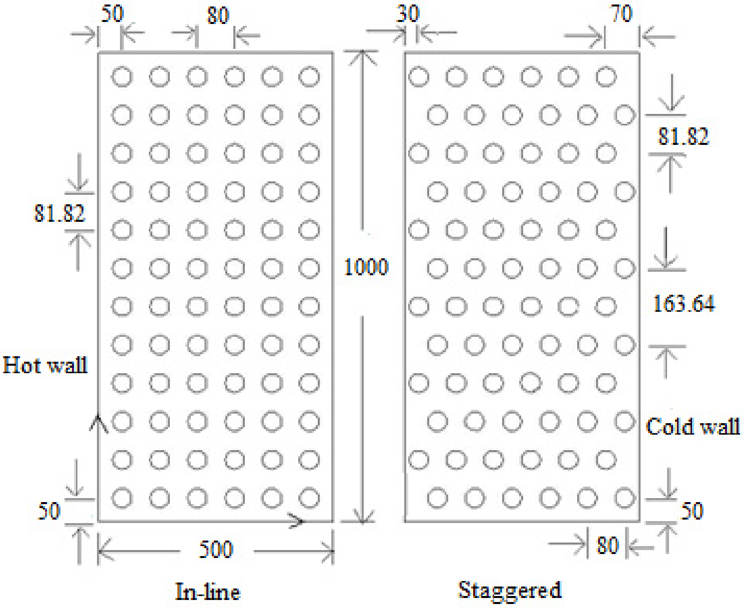


Figure 1: Schematic of the 12 × 6 flow domain arrangement and coordinate system

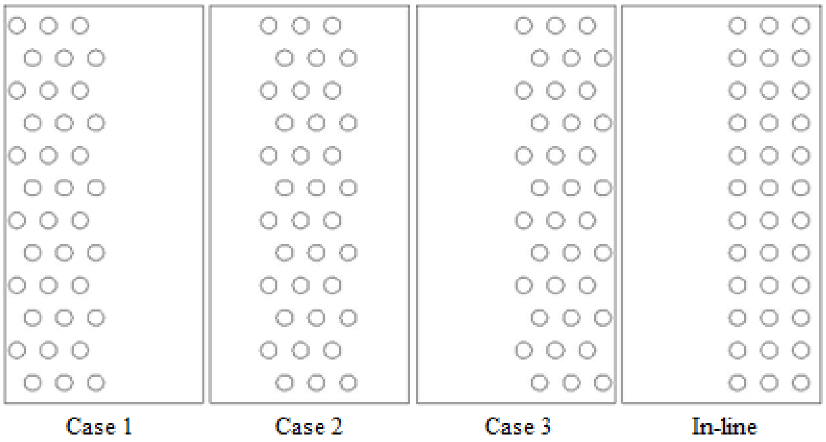


Figure 2: Schematic of the 12x3 arrangement of blockages for staggered and in-line stacking

3. Numerical Method

Calculations were performed for all test cases using the commercial CFD package of ANSYS FLUENT 14.5 [18]. Turbulent fluxes of momentum and heat were modelled by low Reynolds number k-ε eddy viscosity model of Launder-Sharma with the inclusion of the buoyancy terms in the energy equation. This model has been used for greater stability and superior results for blockage flow as reported by Draco et al. [15].

Systematic grid dependency tests were carried out for all cases and the final results were obtained with $y^+ \approx 2$. It is worthwhile to note that the process of computing a steady-state solution using very fine mesh has been quite challenging because of the oscillations associated with higher-order discretization schemes. As a result, a number of steps were taken to achieve a steady-state solution. Initially, low value of Rayleigh number (10^6) was adopted for the solution using an incompressible unsteady solver with a time step of 0.002s with the first-order scheme for convection terms. The resulting data files for the three cases were then used as an initial guess for the higher Rayleigh number simulation using the higher-order discretization schemes. This method helped to create a more realistic initial field for the LR *k-ε* runs. All simulations were performed using a single Intel core 2Duo E6600 2.4 GHZ processor and a typical run took about 0.5 hours of computing time.

Zero heat flux (W/m²) was used as the boundary condition for the passive horizontal walls, while the active vertical walls were maintained at 65.5 ºC and 23.3 ºC for the hot and cold walls respectively. At the surface of the cylinders, zero heat flux (adiabatic surface temperature) was used as the thermal boundary condition. However, radiation heat transfer between the surfaces was taken into consideration. No slip boundary conditions have been imposed for all the solid surfaces. All walls have a fixed emissivity of 0.09, except for the blockages whose emissivity was fixed at 0.9. Thermal properties of the air were estimated at the mean temperature of the isothermal walls of the rectangular enclosure (44.4 ºC). Boussinesq approximation was used to specify air density variation due to temperature [19]. The relative variation of density is less than 3% inside the enclosure. To simulate radiation, Discrete Ordinate Method (ANSYS, 2013) has been chosen.

4. Results and Discussion

The numerical results and analyses are presented in this section. At steady state, heat transfer and flow parameters such as the temperature, velocity and turbulence profiles along the mid-height (y/H=0.5) and mid-width (x/L=0.5) were collected and analysed. For all cases, temperature data for the mid-height and mid-width displays a stable core region and hence emphasis is placed on profiles near the walls. The numerical results using the current methodology has already been thoroughly scrutinised and validated against reliable experimental data [17, 18] and hence excluded from this paper.

4.1. The 12×6 arrangements

The influence of staggered arrangement of blockages on the flow and heat transfer is analysed by comparing the results with in-line arrangements. Figure 3 shows the temperature profile at mid-width and near the bottom part of the cavity. A nearly similar pattern is observed for the top part and hence is omitted to avoid repetition. The change in temperature between the two configurations is significant especially near the passive horizontal walls, with a maximum of about 2.5 ºC and is found to occur within the boundary layer. The effect due to staggering is more prominent up to y/H=0.15 after which a stable core region can be seen. The turbulence intensity for the two configurations is shown in Fig. 4. It can be observed that the effect is very prominent on turbulence intensity. The average Nusselt number for the two configurations presented in Table 1 shows that the staggering reduces the heat transfer by a modest 7%.

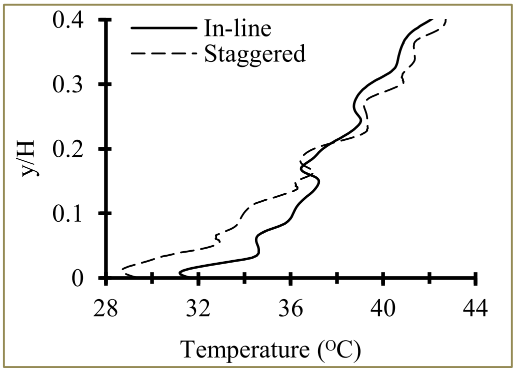


Figure 3: Near bottom wall temperature profile at mid-width

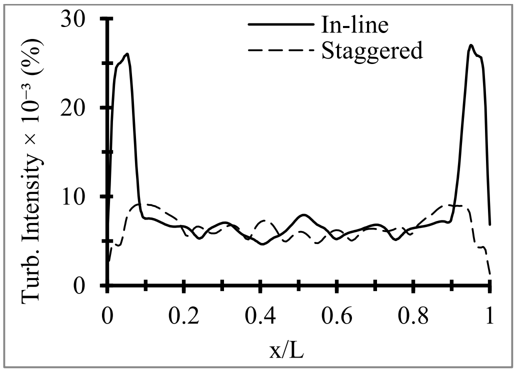


Figure 4: Turbulence intensity profiles at mid-height

Table 1: Average Nusselt number comparison

	Average Nusselt number (12×6)	
	In-line	Staggered stacking
Hot wall	75.30	69.57
Cold wall	73.99	68.38

4.2. The 12×3 arrangements

The results for the in-line and staggered 12×3 arrangement of blockages are presented in this section. For both arrangements, three different cases have been considered as shown in Fig. 2. Firstly, results are presented for in-line stacking and secondly, the effects due to staggering are specifically addressed by suitable plots.

4.2.1. In-line stacking arrangement

Figures 5 show the temperature profiles at mid-height of the cavity, with Case 3 showing the maximum temperature. The average temperature difference between Case 3 and Case 1 is about 2.4 °C for the most part of the mid-height plane. Similar plot in Fig.6 shows the turbulence intensity profiles highlighting the fact that the proximity of blockages is closely linked to the suppression of turbulence and is also in conformity with the heat transfer through the active walls as presented in Table 2. It is hence reasonable to imply that the different stacking of blockages within an enclosed space can lead to a significant change in the heat transfer, and in our case, the average change in heat transfer is about 10.5%.

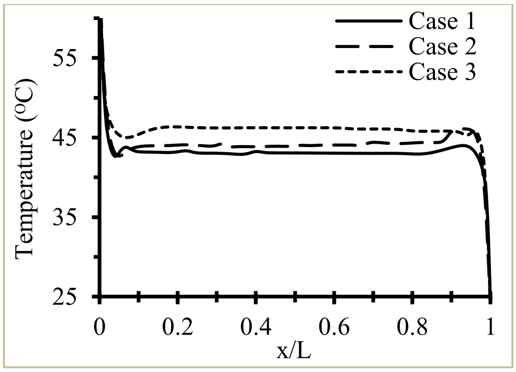


Figure 5: Temperature profile at mid-height

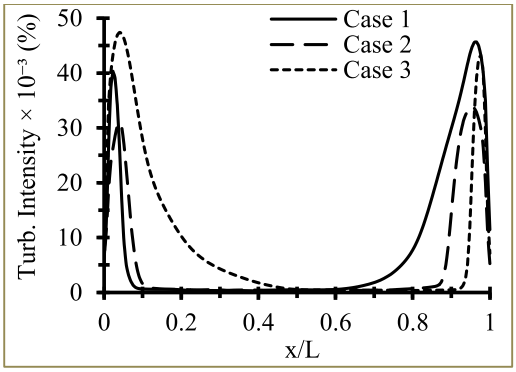


Figure 6: Turbulence intensity profile at mid-height

Table 2: Average Nusselt number comparisons (In-line stacking)

	Average Nusselt number (12×3)		
	Case 1	Case 2	Case 3
Hot wall	78.01	77.80	87.16
Cold wall	87.47	76.75	77.07

4.2.2. Comparison of in-line and stacking 12×3 arrangements

In this section, we compare the results for in-line and staggered stacking of 12×3 blockage arrangements. Figure 7 shows a sample of the flow pattern in the form of a stream function plots for the three different stacking conditions. Overall, the flow field is dominated by stacking arrangement with the main fluid motion taking place near the walls. As expected, the stacking arrangement of Case 1 and Case 3 shows a diagonally symmetric flow pattern. On the other hand, Case 2 displays a rather trapezoidal core region with the higher flow velocities squeezed toward the top right hand and bottom left hand corners of the enclosure.

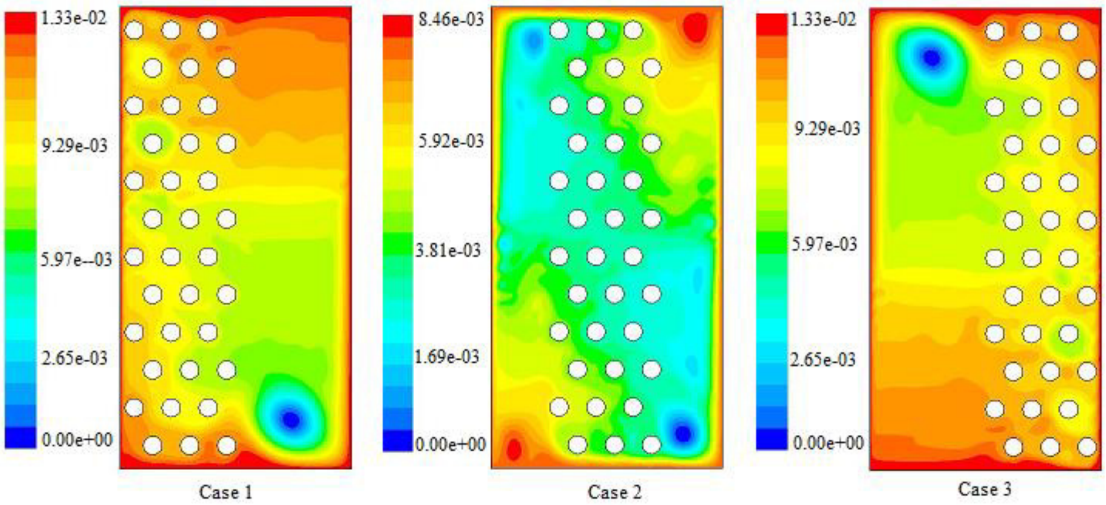
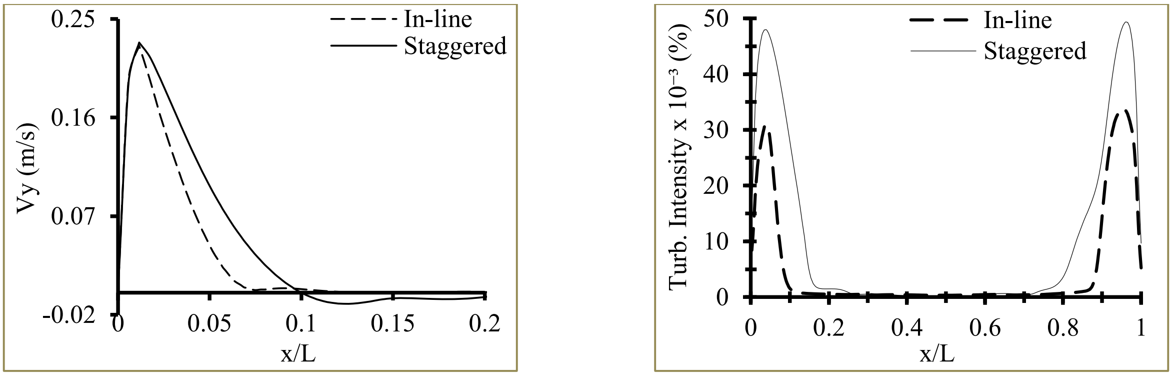


Figure 7: Stream function plots for the three cases of stacking conditions.

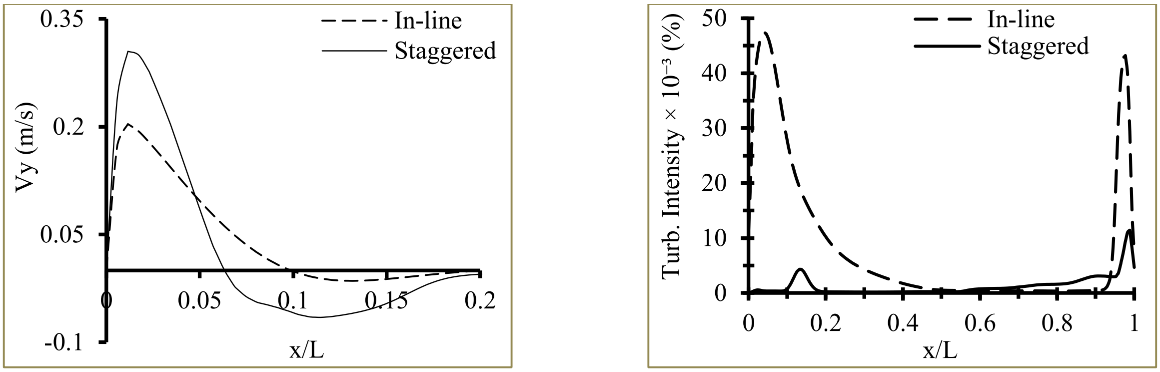
Figures 8-9 compare the vertical component of velocity, Vy, and turbulence intensity profiles at the mid-height for Cases 2 and 3. For Case 2, the maximum velocity does not show any significant variation due to arrangement. However, turbulence intensity shows sensitivity which is similar to the previous situation. For Case 3, the velocity magnitude is found to be affected and is due to the very different vortex pattern thanks to the particular stacking arrangement. Again, the turbulence intensity can be seen to be drastically reduced due to the staggering of blockages.



(a) (b)

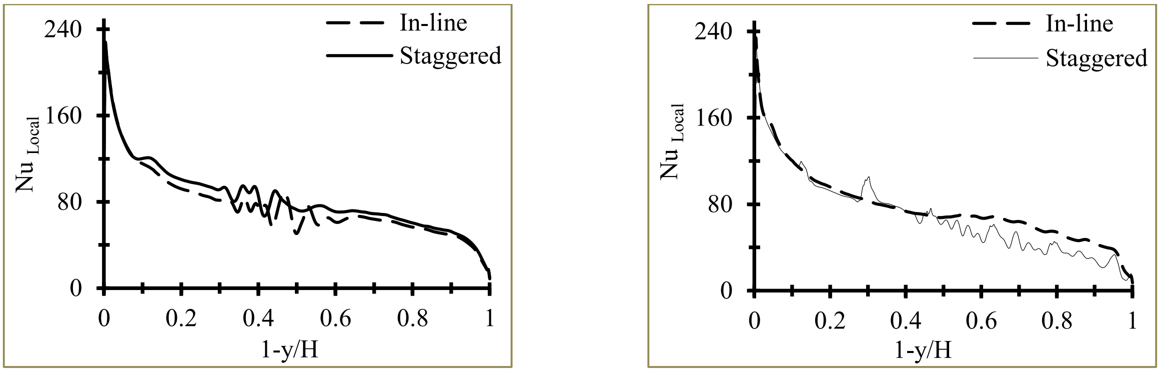
Figure 8: (a) Vertical velocity and (b) turbulence intensity at mid-height for Case 2

The relative influence on wall heat transfer in terms of local Nusselt numbers within the enclosure are shown in Fig.10. For the case of the blockage stacking near the active vertical walls (Case 3), the in-line configuration shows a higher heat transfer as compared to the staggered configuration. It was also calculated that the average heat transfer for the staggered arrangements were lower by up to 16% in comparison with the in-line stacking.



(a) (b)

Figure 9: (a) Vertical velocity and (b) turbulence intensity at mid-height for Case 3



(a) (b)

Figure 10: Local Nusselt number comparisons at cold wall (a) Case 2 (b) Case 3

5. Conclusion

Based on the calculations carried out in this research programme, the numerical results allow a better understanding on the influence of blockages arrangement within a low turbulent natural convection flow in an enclosure. The influence on fluid flow and heat transfer for the different stacking of arrangement of the blockages within the enclosure was identified and detailed profiles at the mid-height and mid-width of the rectangular enclosure have been analyzed. Some general conclusions are presented below:

a) Temperature stratification was observed in all cases, high temperature at the top and low temperature at the bottom region of the enclosure.
b) The flow in such a low temperature enclosure is sensitive to the different stacking arrangement of products and hence a detailed understanding of the flow physics is important for an enhanced design of such applications.
c) The average heat transfer in the enclosure can be reduced to about 16% due to the pattern of arrangement. The stacking pattern was found to affect the flow and heat transfer fairly modestly which is probably dominated by

the suppression of turbulence near the walls. The variation of temperature and heat transfer is modest and hence may be very important in the design of practical applications where long term exposure is in place.

6. References

[1] S. Kadem, A. Lachemet, R. Younsi, and D. Kocaefe, "3d-Transient modeling of heat and mass transfer during heat treatment of wood," *International Communications in Heat and Mass Transfer,* vol. 38, pp. 717-722, Jul 2011.

[2] O. Laguerre, S. Benamara, D. Remy, and D. Flick, "Experimental and numerical study of heat and moisture transfers by natural convection in a cavity filled with solid obstacles," *International Journal of Heat and Mass Transfer,* vol. 52, pp. 5691-5700, Dec 2009.

[3] B. Calcagni, F. Marsili, and M. Paroncini, "Natural convective heat transfer in square enclosures heated from below," *Applied Thermal Engineering,* vol. 25, pp. 2522-2531, Nov 2005.

[4] Y. S. Tian and T. G. Karayiannis, "Low turbulence natural convection in an air filled square cavity - Part II: the turbulence quantities," *International Journal of Heat and Mass Transfer,* vol. 43, pp. 867-884, Mar 2000.

[5] F. Ampofo and T. G. Karayiannis, "Experimental benchmark data for turbulent natural convection in an air filled square cavity," *International Journal of Heat and Mass Transfer,* vol. 46, pp. 3551-3572, Sep 2003.

[6] A. A. DafaAlla and P. L. Betts, "Experimental study of turbulent natural convection in a tall air cavity," *Experimental Heat Transfer,* vol. 9, pp. 165-194, Apr-Jun 1996.

[7] F. Penot, O. Skurtys, and D. Saury, "Preliminary experiments on the control of natural convection in differentially-heated cavities," *International Journal of Thermal Sciences,* vol. 49, pp. 1911-1919, Oct 2010.

[8] W. Chen and W. Liu, "Numerical and experimental analysis of convection heat transfer in passive solar heating room with greenhouse and heat storage," *Solar Energy,* vol. 76, pp. 623-633, 2004.

[9] D. Saury, N. Rouger, F. Djanna, and F. Penot, "Natural convection in an air-filled cavity: Experimental results at large Rayleigh numbers," *International Communications in Heat and Mass Transfer,* vol. 38, pp. 679-687, Jul 2011.

[10] G. Barakos, E. Mitsoulis, and D. Assimacopoulos, "Natural-Convection Flow in a Square Cavity Revisited - Laminar and Turbulent Models with Wall Functions," *International Journal for Numerical Methods in Fluids,* vol. 18, pp. 695-719, Apr 15 1994.

[11] G. D. McBain, "Natural convection with unsaturated humid air in vertical cavities," *International Journal of Heat and Mass Transfer,* vol. 40, pp. 3005-3012, Sep 1997.

[12] G. Desrayaud and G. Lauriat, "Heat and mass transfer analogy for condensation of humid air in a vertical channel," *Heat and Mass Transfer,* vol. 37, pp. 67-76, Jan 2001.

[13] M. K. Das and K. S. K. Reddy, "Conjugate natural convection heat transfer in an inclined square cavity containing a conducting block," *International Journal of Heat and Mass Transfer,* vol. 49, pp. 4987-5000, Dec 2006.

[14] H. S. Yoon, D. H. Yu, M. Y. Ha, and Y. G. Park, "Three-dimensional natural convection in an enclosure with a sphere at different vertical locations," *International Journal of Heat and Mass Transfer,* vol. 53, pp. 3143-3155, Jul 2010.

[15] D. A. Iyi, R. Hasan, and R. Penlington, "Interaction effects between surface radiation and double-diffusive turbulent natural convection in an enclosed cavity filled with solid obstacles," *ICHMT Digital Library Online,* 2012.

[16] D. Iyi, R. Hasan, and R. Penlington, "Numerical Simulation of 2D Turbulent Natural Convection of Humid Air in a Cavity Filled with Solid Objects," *Procedia Engineering,* vol. 56, pp. 538-543, // 2013.

[17] D. Iyi, R. Hasan, and R. Penlington, "Effect of Emissivity on Heat and Mass Transfer of Humid Air in a Cavity Filled with Solid Obstacles," *Numerical Heat Transfer, Part A: Applications,* vol. NHT13/5995, 2014.

[18] ANSYS Inc., "ANSYS Fluent 14.5.," 2013.

[19] H. K. Versteeg and W. Malalasekera, *An introduction to computational fluid dynamics: the finite volume method*: Pearson Education, 2007.