Hittite Journal of Science and Engineering, 2019, 6 (1) 17-23
ISSN NUMBER: 2148-4171
DOI: 10.17350/HJSE19030000128

Effects of Arc-Shaped Partitions in Corners of A Shallow Cavity on Natural Convection

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Article History:
Received: 2017/12/11
Accepted: 2018/10/14
Online: 2019/01/31

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ABSTRACT

In this study, a numerical analysis carried out to determine the effects of arc-shaped partitions in corners of a shallow cavity on heat transfer which is natural convection and fluid flow. Partitions are accepted as conductive and two different partitions materials are chosen as wood and aluminum. The finite volume approach is used to discretize the governing equations for Rayleigh numbers (Ra) and shape ratio of the arc-shaped partition. It is found that arc-shaped partitions have effect on characteristic parameters of fluid flow and heat transfer. Specially, aluminum arc-shaped partition affects the average heat transfer enhancement, because it has high heat transfer coefficient. Also, possibilities of occurring dead regions are examined and streamlines obtained for without partitions and high Rayleigh numbers which are $Ra=10^5$ and $Ra=10^6$ show that dead regions occur in corners of the shallow cavity. Results obtained from the analysis using partitions and considering different Rayleigh numbers and partition materials show that using partition which is arc-shaped prevent occurring dead regions.

Keywords:
Natural convection; Conjugate heat transfer; Heat transfer; Shallow cavity; Arc-shaped.

INTRODUCTION

Natural convection phenomena occurs in nature and different applications. Specially, in the cooling of electronic devices is gaining importance. In the recent years, different projects and designs for natural convection applications have been performed. In the natural convection investigations, many different geometries were examined. In the last trend about this phenomena, partitions have been placed at corner or edge of the geometry. These studies were considered square cavity and examined many different parameters related to heat transfer and fluid flow. The square cavity is most popular geometric shape than shallow cavity in the similar analysis. However, studies about shallow cavity placed different shape partitions have been raised. Some of them in the literature were considered in this part of the study. Polat and Bilgen [1] focused on natural convection in inclined shallow cavities, in their study. They heated the side facing the opening a constant heat flux, insulated sides perpendicular to the heated side. The authors solved equations of mass, energy and momentum considering steady state conditions and Boussinesq approximation. They calculated heat and mass transfer for Rayleigh number from 10^3 to 10^{10}. Shiralkar and Tien [2] studied on heat transfer in a horizontal cavity. The authors considered as adiabatic walls which are horizontal and isothermal side walls of the horizontal cavity for different aspect ratios. Drummond and Korpela [3] studied on natural convection in a shallow enclosure. Only one side of the shallow enclosure was heated. Top and bottom walls were considered as both insulated and conducting. Paolucci and Chenoweth [4] studied on a rectangular cavity for determining heat transfer characteristics. Their problem was two dimension and they considered different aspect ratios and Rayleigh numbers for solution parameters which are Nusselt numbers, temperature and velocity distributions. Zhang et al. [5] studied on a vertical rectangular for determining temperature distribution, the flow characteristics, and the overall heat transfer rate. Novak and Nowak [6] studied on theoretically natural convection in a cavity with different aspect ratios. They used the finite difference technique in their study. Bhave et al.

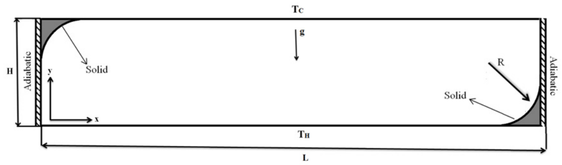
[7] studied on a square enclosure by using finite volume formulation. They solved governing equations which are mass, momentum and energy via using that numerical method. The problem was considered as two dimensional for determining heat transfer characteristics which is natural convection. Horizontal walls and vertical walls of the enclosure were considered as adiabatic and differentially heated, respectively. Karatas and Derbentli [8] studied the natural convection inside the vertical shallow cavity. Benos et al. [9] performed a work on natural convection in the shallow cavity which is horizontal. Alloi and Vasseur [10] studied the natural convection in a shallow cavity in the presence of micropolar fluids. Also, Alloi et al. [11] tested the natural convection phenomena in the presence of nanofluid for shallow cavities.

This study is to make a control of different parameters in a shallow cavity by inserting arc-shaped passive equipment to the corner. Thus, energy efficiency will be increase due to ignored of dead regions at the corners. In the analysis, different parameters are considered. These parameters are the arc-shape aspect ratios which is symbolized as R, different Rayleigh numbers from $Ra=10^4$ to $Ra=10^6$, different partition materials which are wood and aluminum. About detail solution method and approach are expalined next part of this study.

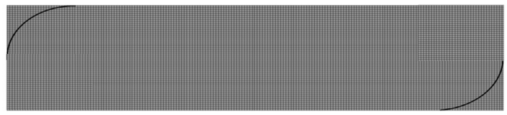
MATERIAL AND METHODS

The physical model is presented in Fig. 1 (a) where boundary conditions shows. It is a shallow cavity with H<L and horizontal wall has an isothermal heaters. Vertical walls are considered as adiabatic. Bottom wall of the shallow cavity is defined steady temperature boundary condition which is symbolized as T_H, and temperature value of the top wall is lower than bottom wall. The temperature of the top wall is indicated as T_C. The shallow cavity has two arc-shaped partitions that these partitions made from different materials. In Fig. 1 (a), g is gravity and R is aspect ratio of the of the arc-shape partitions. Thus, they have different thermal conductivity values. The radius of conductive material is changed as a governing parameter on fluid flow and heat transfer. Fig. 1 (b) shows grid distribution of the shallow cavity.

The governing equations are based on the conservation laws. While the energy equation was written, Boussinesq approximation was considered. It means that fluid properties which is physical are considered as constant, but density of the fluid change in body force term of the momentum equation. Viscous dissipation is neglected and, radiation heat transfer and pressure work are neglected too. The finite volume method is used to solve the governing equations. The SIMPLE algorithm is used to treat the pressure term



a)



b)

Figure 1. a) Shallow cavity, b) Grid Distribution

[12]. QUICK scheme [13] is used for the discretization of the convective terms in the momentum and energy equations. The calculations are done using FLUENT [14] commercial software. Considering with these assumptions, the governing equations can be written as,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

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

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+g\beta(T-T_c) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

For solid region, the governing equation can be considered Eq. (5).

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=0 \tag{5}$$

The governing equations in terms of velocity and pressure can be written in a dimensionless form as,

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{6}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{7}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+Ra\Pr\theta \tag{8}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{9}$$

For solid region,

$$\frac{\partial^2 \theta}{\partial x^2}+\frac{\partial^2 \theta}{\partial y^2}=0 \tag{10}$$

For dimensionless variables, Eq. (11) can be used:

$$X=\frac{x}{L},\ Y=\frac{y}{L},\ U=\frac{uL}{\alpha},\ V=\frac{vL}{\alpha},\quad P=\frac{(p+\rho g y)L^2}{\rho v^2},\ \theta=\frac{T-T_c}{T_h-T_c} \tag{11}$$

Boundary conditions for walls are follow as,

$$X=1,\ 0\le Y\le 1,\ U=0,\ V=0,\ \theta=1 \tag{12}$$

$$X=0,\ 0\le Y\le 1,\ U=0,\ V=0,\ \theta=0 \tag{13}$$

$$0\le X\le 1,\ Y=0,\ U=0,\ V=0,\ \frac{\partial\theta}{\partial Y}=0 \tag{14}$$

The thermal boundary condition for conductive of the arc-shaped partition is written as,

$$k_{fluid}\left(\frac{\partial\theta}{\partial n}\right)_{\text{fluid}}=k_{\text{solid}}\left(\frac{\partial\theta}{\partial n}\right)_{\text{solid}} \tag{15}$$

$$T_{\text{fluid}}=T_{\text{solid}} \tag{16}$$

Prandtl number, Grashof number and Rayleigh number are given as

$$\Pr=\frac{\upsilon}{\alpha},\ Gr=\frac{g\beta\Delta TH^3}{\upsilon^2},\ Ra\ =\ Gr\cdot Pr \tag{17}$$

The detail information about the method, algorithm and using software can be found in references [12 – 14]. The Nusselt numbers which are local and aveage are calculated by using Eqs. (18) and (19).

$$Nu=-\left.\frac{\partial\theta}{\partial X}\right|_{X=0} \tag{18}$$

$$Nu_{ave}=\int_0^H Nu_w dy \tag{19}$$

The present code is validated by earlier works to supply the validity of the code. In this case, the study is performed for the same Rayleigh number with literature and differentially heated cavity without any partition. Average Nusselt numbers are calculated and compared with two different works in the literature as shown in Table 1.

As can be seen in Table 1, results obtained show good agreement with literature [15, 16]. Fluid flow and natural convection characteristics are determined in the physical model which is shallow cavity. Many different parameters are considered for using with and without partitions, and these parameters are streamlines, local and average Nusselt number, temperature distribution inside of the shallow cavity. These results are shared in next section.

Table 1. Average Nusselt number

Nu	*Ra=10⁴*	*Ra=10⁵*	*Ra=10⁶*
DC Wan et al. [15]	2.254	4.598	8.976
G Barakos et al. [16]	2.245	4.510	8.806
Present Study	2.235	4.509	8.904

RESULTS AND DISCUSSION

In this study, a numerical analysis carried out to determine the effects of arc-shaped partitions in corners of a shallow cavity on heat transfer which is natural convection and fluid flow. Partition shapes are made from aluminum and wood. Aluminum is used for many heat transfer applications due to having high thermal conductive. Materials which have low thermal conductive are used for heat transfer control. In this perspective, wood is chosen as material having low thermal conductive and effects of these materials on heat transfer and fluid flow characteristics are examined and compared. The effects of the varying Rayleigh number on the distributions which are streamline and isotherm are demonstrated in Fig. 2-4 for without partitions, wood and aluminum partition (R=1.1) cases.

Temperature values unit in the isotherms is Kelvin. As

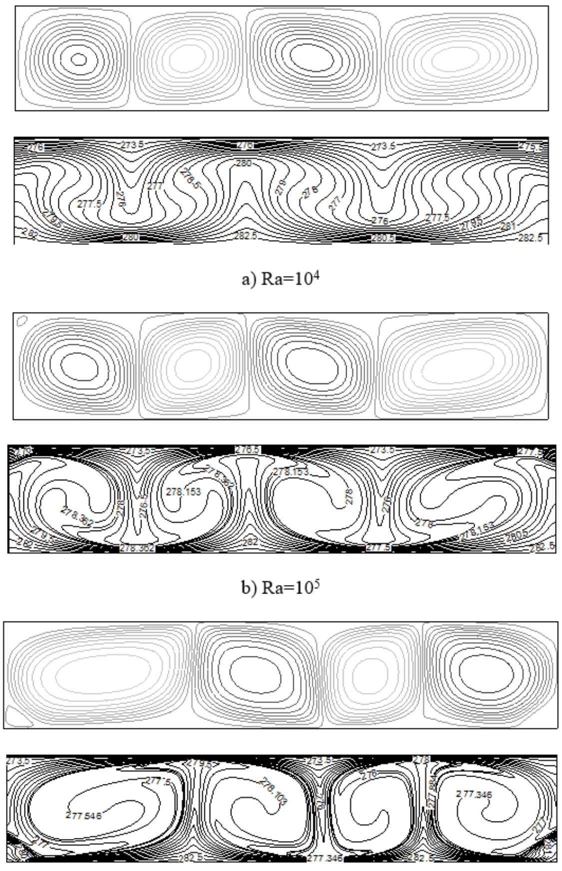


Figure 2. Streamlines (on the top) and isotherms (on the bottom) without partition for various Rayleigh numbers

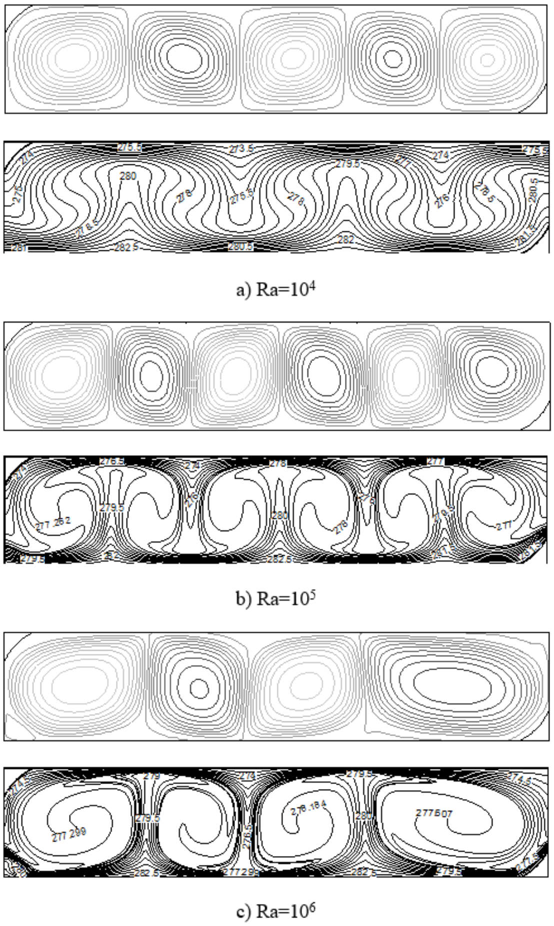


Figure 3. Streamlines (on the top) and isotherms (on the bottom) with aluminum partition for various Rayleigh numbers, R=1.1

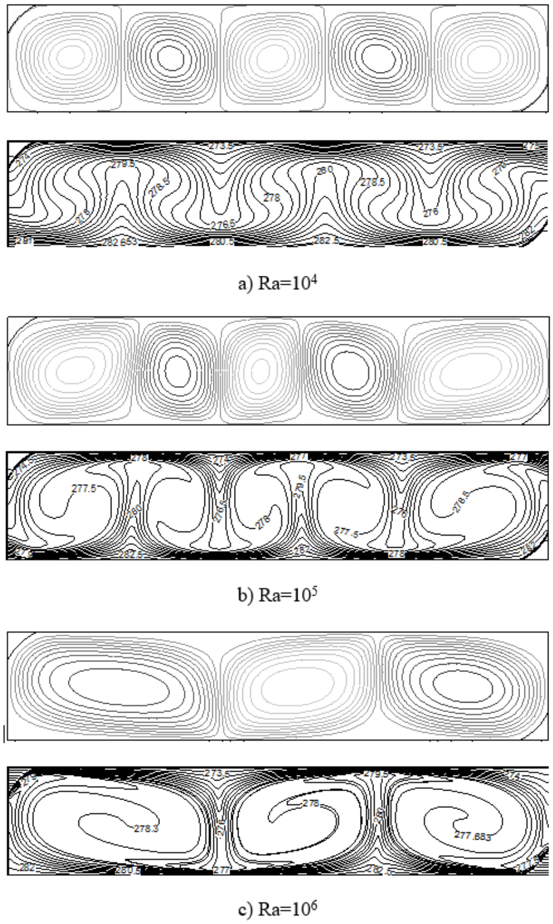


Figure 4. Streamlines (on the top) and isotherms (on the bottom) with wood partition for various Rayleigh numbers, R=1.1

can be seen at streamlines in Fig. 2, the results obtained from the analysis show that dead regions at the corners occur for $Ra=10^5$ and $Ra=10^6$. Fig. 3 shows results obtained from the streamlines and isotherms with aluminum partition for different Ra numbers.

In the Fig. 3, dead region occur only for $Ra=10^6$ and R=1.1. This result shows that dead region can be prevent by using partition, but dead region can occur based on flow characteristic in corners where partition is not placed.

The number of cells is four within the cavity for the case without partition and, when the Rayleigh number increases, the strength of the natural convection increases. The shape of the cells gets distorted in different directions with increasing the Rayleigh number and isotherms are affected due to increasing convection effects of buoyancy. Adding a partition effects the number of cells and temperature distribution within the cavity as can be seen in Figs. 3-4. When the aluminum partition is used, the number of cells is first increased to six and then decreased to four with increasing the Rayleigh number. When the wood material is used the number of cells is decreased to three for the highest Rayleigh number of interest. The effects of Ra number on the local Nu number distributions are depicted in Fig. 5.

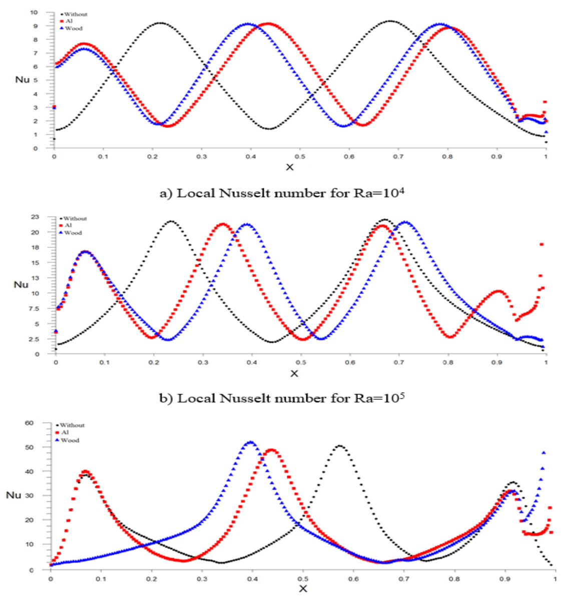


Figure 5. Variation of local Nusselt Number along the horizontal direction for various Rayleigh numbers, R=1.1

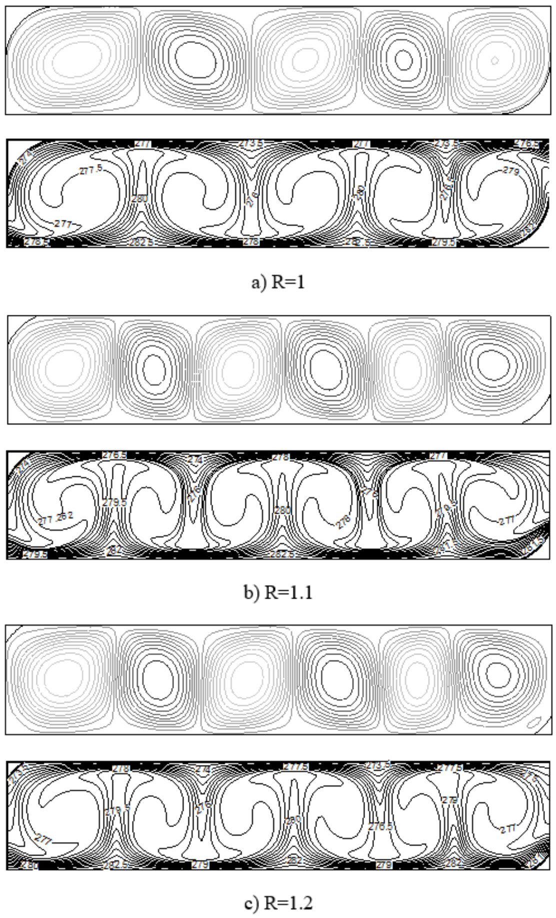


Figure 6. Effects of curvature on the streamlines (on the top) and isotherms (on the bottom) with aluminum partition, Ra=10^5

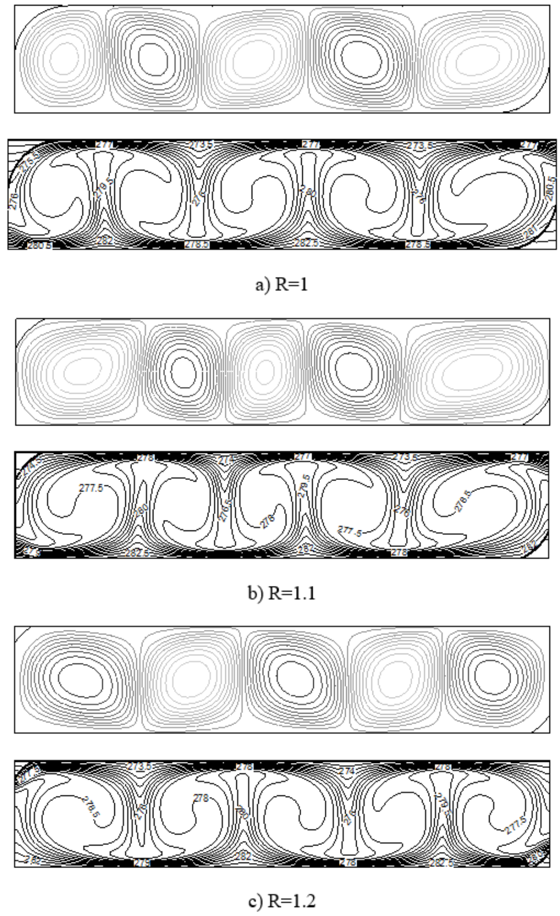


Figure 7. Effects of curvature on the streamlines (on the top) and isotherms (on the bottom) with wood partition, Ra=10^5

The number of peaks in the Nusselt number increases with the addition of the partition due to the increased number of cells at Ra=10^4 and Ra=10^5. The discrepancy between the aluminum and wood partition is more visible at Ra=10^6. Effects of the curvature of the partition are presented in Fig. 6 for aluminum and in Fig. 7 for wood partition (Ra=10^5).

The results obtained from the analysis show that dead regions at the corners occur for Ra=10^5 and Ra=10^6. The dead region occurs only for Ra=10^6 and R=1.1 and dead regions are not seen in all others situations which are used partitions. When the radius of the curvature increases, the number of the cells is increased from five to six for aluminum partition. The size and strength of the cells on the left and right ends of the cavity decrease as the radius of the curvature increases for the aluminum partition. When the wood partition is used in Fig. 7, although the number of cells remains the same, the size of the cells on the left and right ends of the cavity first increases then decreases when the radius of the curvature is increased. Fig. 8 demonstrates the effect of varying the radius of curvature on the local Nu number along the horizontal wall of the cavity at Ra=10^5.

In all situations which are placed partition, local Nusselt number values increase. As can be seen in the figures

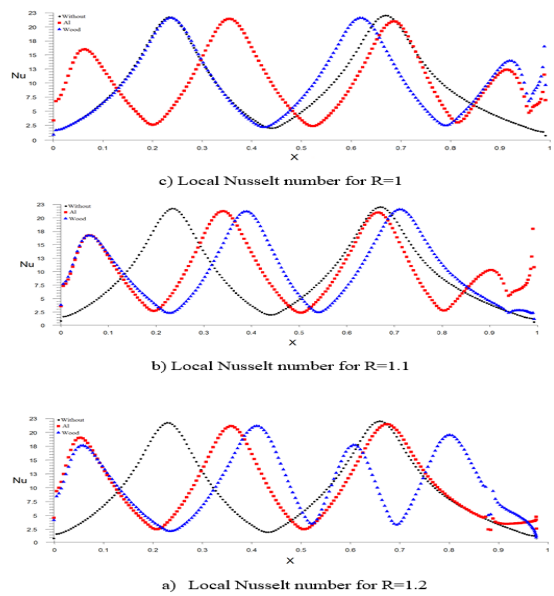


Figure 8. Variation of local Nusselt Number along the horizontal direction for various radius of curvature, Ra=10^5

Table 2. Average Nu

R	Ra=10^4		Ra=10^5		Ra=10^6	
	Average Nu_{ave}		Average Nu_{ave}		Average Nu_{ave}	
	Al	Wood	Al	Wood	Al	Wood
0	5.05	5.05	9.63	9.63	16.809	16.809
1	5.763	5.656	11.264	11.28	20.076	19.327
1.1	5.542	5.54	10.456	10.629	16.762	14.956
1.2	5.439	5.23	10.524	10.15	17.141	18.361

related to local Nusselt number, local Nu value changes along the x-axis. Especially, local Nu numbers are very variable at origin of x and y axis (x=0 and y=0) and end of the x axis. The partition which is arc-shaped causes this variable. For example, when results obtained all situations which are both with and without partition are compared, effects of without partition can be shown in the local Nusselt numbers obtained from without partition situation. The local Nusselt number values change between 1 and 50 for R=1.1 and Ra=10^6. Also, the local Nu values change between 1 and 9 for R=1.1 and Ra=10^4. The number of peaks increases when the partition is added due to the increased number of cells for R=1 and R=1.1. The discrepancy between the aluminum and wood partition is more apparent for R=1.2. The radius of curvature and thermal conductivity of the partition can be used as passive element to control the heat transfer and fluid flow within the cavity. Average Nusselt number values allow us to make a general assessment about results obtained from this study. Averaged Nusselt numbers along the horizontal wall of the cavity are shown in Table 2.

Adding a partition enhances the heat transfer. At Ra=10^4 and Ra=10^5, averaged heat transfer decreases as the radius of curvature increases for aluminum and wood partitions. At the highest Rayleigh number of interest, an increase and then a decrease in the averaged heat transfer is seen as the radius of curvature increases. When the average Nu number is considered with and without partitions, heat transfer increasing rate is determined as 12.37% for R=1, using aluminum partition and Ra=10^4. In this perspective and similar conditions, heat transfer increasing rate is calculated as 10.71% for using wood partition. When values obtained for R=1.2 and Ra=10^6 are considered, rates of increase in heat transfer for without partition and using aluminum and wood partitions are 1.93% and 8.45%, respectively. The greatest rate of increase in heat transfer is obtained for R=1, using aluminum partition and Ra=10^6. In these conditions, rate of increase in heat transfer is calculated as 16.27%. For using wood partition, rate of increase in heat transfer is determined as 13.02% in same conditions. It can be said that using partition in shallow cavity increases heat transfer rate in all of conditions of Ra=10^4. Results obtained for R=1.1 and Ra=10^6 show that heat transfer decrease. Rate of decrease in heat transfer for using aluminum partition and R=1.1 at Ra=10^6 is 0.27% and in similar conditions, rate of decrease in heat transfer for using wood is 11.02%. When aluminum and wood partition are compared, aluminum shows better results than wood. However results obtained from situation using wood partition show that material having low thermal conductive can be used for heat transfer control. Especially, results obtained from this study can be considered in applications which are cooling of electronic devices, conditioning of rooms and so on. When streamlines obtained from the analysis which are with and without partitions are examined, the partitions effect on fluid flow characteristic as well as heat transfer. While four cell occur in the streamlines obtained for without partition and Ra=10^4, Ra=10^5 and Ra=10^6, different cells are obtained for with partitions. For example, five cell occur at result obtained for Ra=10^4 and aluminum, six and four cell occur for Ra=10^5, Ra=10^6 and aluminum, respectively. As can be seen in Fig. 4, five and three circular flow occur for using with wood partition and Ra=10^4, Ra=10^5 and Ra=10^6 in the streamlines. The heat transfer and fluid flow characteristics strongly influenced depending on these parameters which are using partition and partition material type, Ra and R.

CONCLUSION

Numerical study of natural convection in arc-shaped partitions in corners of a shallow cavity filled with air was performed. The effects of arc-shaped partitions in corners of a shallow cavity on heat transfer which is natural convection and fluid flow. Partitions are accepted as conductive and two different partitions materials are chosen as wood and aluminum. Also, possibilities of occurring dead regions are examined and streamlines obtained for without partition and high Rayleigh numbers which are Ra=10^5 and Ra=10^6 show that dead regions occur in corners of the shallow cavity. Some important conclusion can be indicated from this numerical study as:

- Characteristic parameters of the flow and heat transfer are affected by adding a arc-shaped partitions to the shallow cavity.

- Curvature of the partition affects the average heat transfer enhancement and this can be used as control parameter.

- The results obtained from the analysis show that dead regions at the corners occur for $Ra=10^5$ and $Ra=10^6$. The dead region occur only for $Ra=10^6$ and R=1.1 and dead regions are not seen in all others situations which are used partitions.

- Results obtained from the analysis using partitions and considering different Rayleigh numbers and partition materials show that using partition which is arc-shaped prevent occurring dead regions.

- At $Ra=10^4$, heat transfer enhancements of 14%, 9.74% and 7.7% were obtained for R=1, R=1.1 and R=1.2 compared to flat cavity. These results were obtained for aluminum arc-shaped partition. In the same conditions and for wood arc-shaped partition, heat transfer enhancements of 12%, 9.7% and 3.36% were obtained.

The different materials can be used as partitions and many different parameters can be examined considering Ra, R, fluid and so on. In this study, fluid is air but different studies can be carried out by using nanofluid. Also, this problem can be considered for unsteady flow.

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