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Investigation of Discrete Heating At Upper Section of A Porous Annulus

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ABSTRACT

Heat transfer in porous medium is one of the important area of research from engineering and scientific point of view. The present research highlights the heat transfer characteristics in a vertical porous annulus having porous medium fixed between its inner and our radii. An upper section of the annuls is heated isothermally to constant temperature Tw and outer radius is cooled at lower temperature T∞. Finite Element Method is utilised to solve the governing partial differential equations. Two temperature model is used to represent thermal non-equilibrium among solid and fluid phases of porous medium. The study is conducted for different lengths of heater corresponding to the 20%, 35% and 50% of the total height of the cylinder.It is found that the average Nusselt number increases with increase in heater length.

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INTRODUCTION

The last century has seen phenomenal growth in the research of porous medium ever since the emergence of classical work of Henry Darcy. The porous media plays a vital role in many of the scientific and engineering applications such as flow through the crest of the earth, heat exchangers, waste disposal, electronic components, storage devices etc. thus justifying its immense interest among scientific community. Heat transfer sets up the fluid trapped in porous medium to move causing the heat to be transported by conduction within solid matrix and by convection across fluid as well as fluid solid interaction region.The heat transfer in porous medium in general addresses two kinds of issues. The first kind of issue is the coupling of complex phenomenon for instance, double diffusion (Ching-Yang Cheng, (2010), Mahdy *et al.* (2010), Badruddin *et al.* (2012a)), viscous dissipation (Amgad, (2013), Chen and Tso(2011), Badruddin *et al.*(2006a), Magneto-hydrodynamic flow (Raju(2014), Dessie and Kishan(2014)) etc. and the second issue is geometry of porous medium itself such as porous medium adjacent to vertical plate (Raptis, (1998), Badruddin *et al.* (2006d)) or square cavity (Saeid, N.H., (2005)) or cylindrical geometry (Saeid, N.H., (2006)) etc. in various orientation. The present work is focused to investigate the heat transfer in a porous medium in an annular shape having discrete heating at upper section of inner radius. Generally, there are two approaches to the heat transfer problem in porous medium including the annular geometry. The simpler approach is that the temperature can be assumed to be similar between solid and fluid phases of porous medium as studied by various researchers such as (Prasad and Kulacki (1984), Rajamani, R., *et al.*, (1995), Badruddin, *et al* (2006b, 2007a),Ahmed *et al.* (2009,)). The other approach that is more complex and realistic is to believe that the temperature of solid matrix and fluid phase have discrepancy thus leading to two temperature model of energy equation as dealt by (Saeid, 2006, Ahmed *et al* 2011, Xiao-Long *et al.* 2013)The flow pattern may be affected due to non-uniformity of applied thermal source either in terms of its value or in terms of its location such as particular place or portion of the geometry. In this case the flow pattern and the heat transfer characteristics would get affected in significant manner as obvious from the work of Saha (2010), Tye-Gingras *et al.* (2010), Bilgen and Müftüoglu (2008). Some of the other works in the area of discrete or localized heating includes that of Yan and Lin (1987) Akdag (2010). Tao and Zhang (2003).Fu-Yun *et al.* (2008), Saeid and Pop (2004), Sivakumar *et al.* (2010).Sivasankaran *et al.* (2011),

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Sankar and Do (2010).The authors noticed that there is no literature related to the heater being placed at upper section of annulus. Thus an attempt is made in this work to understand the heat transfer behavior of various heater lengths placed at upper section of annular porous medium. This is an extension of the study for the case when heater is placed at bottom section of the annulus.

2 *Analysis:*

Consider an annular geometry of inner radius r_i and outer radius r_o with porous medium fixed within inner and outer radii as shown in fig 1. The coordinate system is chosen in such a way that the r and z axis points towards the radial and vertical direction of the annulus. An upper section of the inner surface of the annulus is heated to constant temperature Tw and the outer surface is maintained at constant temperature $T\infty$ such that $Tw > T\infty$. The following assumptions are applied:

a) The fluid follows Darcy law.
b) The convective fluid and the porous medium are not in local thermal equilibrium.
c) There is no phase change of the fluid in the medium.
d) The properties of the fluid and those of the porous medium are homogeneous and isotropic.
e) Fluid properties are constant except the variation of density with temperature.
f) The fluid is transparent to radiation.
g) The radiative heat flux in the z-direction is negligible in comparison to that in the *r*-direction.

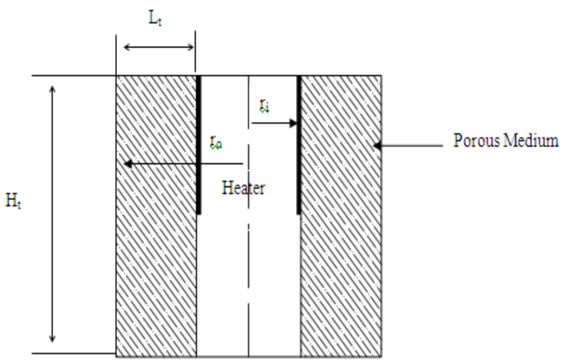

Fig. 1: Schematic diagram of porous annulus.

The final form of non-dimensional equations governing the fluid flow and heat transfer can be given as (Badruddin *et al*; 2006c)

$$\frac{\partial^2 \bar{\psi}}{\partial \bar{z}^2} + \bar{r}\frac{\partial}{\partial \bar{r}}\left(\frac{1}{\bar{r}}\frac{\partial \bar{\psi}}{\partial \bar{r}}\right) = \bar{r} Ra \frac{\partial \bar{T}_f}{\partial \bar{r}} \tag{1}$$

$$\frac{1}{\bar{r}}\left[\frac{\partial \bar{\psi}}{\partial \bar{r}}\frac{\partial \bar{T}_f}{\partial \bar{z}} - \frac{\partial \bar{\psi}}{\partial \bar{z}}\frac{\partial \bar{T}_f}{\partial \bar{r}}\right] = \left(\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\left(1+\frac{4R_d}{3}\right)\bar{r}\frac{\partial \bar{T}_f}{\partial \bar{r}}\right) + \frac{\partial^2 \bar{T}_f}{\partial \bar{z}^2}\right) + H\left(\bar{T}_s - \bar{T}_f\right) \tag{2}$$

$$\left(\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\left(1+\frac{4R_d}{3}\right)\bar{r}\frac{\partial \bar{T}_s}{\partial \bar{r}}\right) + \frac{\partial^2 \bar{T}_s}{\partial \bar{z}^2}\right) = HKr\left(\bar{T}_s - \bar{T}_f\right) \tag{3}$$

Subjected to boundary conditions

at $\bar{r} = r_i$ and $\overline{L_1} \geq \bar{z} \geq \overline{L_2}$, $\quad \bar{\psi} = 0$, $\quad \bar{T}_f = \bar{T}_s = \frac{1}{2}$ (4)

at $\bar{r} = r_o$, $\quad \bar{\psi} = 0$ $\quad \bar{T}_f = \bar{T}_s = -\frac{1}{2}$ (5)

The following parameters have been used for non-dimensionalisation of the governing equations.

$$\bar{r} = \frac{r}{L_{ref}}, \quad \bar{z} = \frac{z}{L_{ref}}, \quad \overline{L_1} = \frac{L_1}{H_t}, \quad \overline{L_2} = \frac{L_2}{H_t}, \quad \bar{\psi} = \frac{\psi}{\alpha \varphi L_{ref}}, \quad \bar{T} = \frac{(T - T_o)}{(T_w - T_\infty)} \text{ where } T_o = \frac{(T_w + T_\infty)}{2}$$

$$R_d = \frac{4\sigma n^2 T_c^3}{\beta_R k_s}, \quad Ra = \frac{g\beta \Delta T K L_{ref}}{\varphi \nu \alpha_f}, \quad H = \frac{h L_{ref}^2}{\varphi k_f}, \quad Kr = \frac{\varphi k_f}{(1-\varphi) k_s} \tag{6}$$

The Nusselt number is calculated using following expressions:
For fluid

$$\bar{N}u_f = -\frac{1}{\left(\bar{L}_2 - \bar{L}_1\right)}\int_{\bar{L}_1}^{\bar{L}_2}\left(\frac{\partial \bar{T}_f}{\partial \bar{r}}\right)_{\bar{r}=\bar{r}_i} d\bar{z} \tag{7}$$

For solid

$$\bar{N}u_s = -\frac{1}{\left(\bar{L}_2 - \bar{L}_1\right)}\int_{\bar{L}_1}^{\bar{L}_2}\left(\left(1+\frac{4}{3}R_d\right)\frac{\partial \bar{T}_s}{\partial \bar{r}}\right)_{\bar{r}=\bar{r}_i} d\bar{Z} \tag{8}$$

The average total Nusselt number is:

$$\bar{N}u_t = \left(\frac{-1}{Kr+1}\right)\frac{1}{\left(\bar{L}_2 - \bar{L}_1\right)}\int_{\bar{L}_1}^{\bar{L}_2}\left\{Kr\left(\frac{\partial \bar{T}_f}{\partial \bar{r}}\right)_{\bar{r}=\bar{r}_o} + \left(1+\frac{4}{3}R_d\right)\left(\frac{\partial \bar{T}_s}{\partial \bar{r}}\right)_{\bar{r}=\bar{r}_i}\right\}d\bar{z} \tag{9}$$

RESULTS AND DISCUSSION

Finite element method is used to convert the governing partial differential equations into algebraic form of equations with the help of a simple 3 noded triangular elements. The accuracy of method is established by comparing the results with previously published data in open literature as shown in table 1. It is obevious that the present method compares well with available literature.

Table 1: Validation of present results.

A_r	Ra	R_r	$\bar{N}u$	
			Rajamani *et al*. (1995)	Present
5	50	0.25	1.619	1.7117
		1	2.105	2.1800
	100	0.25	2.349	2.4596
		1	3.025	3.0859
	200	0.25	3.694	3.7034
		1	4.630	4.5618

Fig.2 depicts the streamlines and isothermal lines when heater is placed at the top section of the annulus. For the values $Ra = 100, Rd = 1, Ar = 2, Rr = 1, H = 100\ and\ K = 1$ maintained as constant. It be noted that the top of the heater always coincides with $\bar{z} = A_r$ for all three heater lengths. It is seen that the fluid moves in two separate regions of the annulus when heater length is 20% of the annuls height. The fluid cell moves from lower part to occupy the whole annulus as the length of the heater increases. The fluid movement changes the shape from being circular at HL=20% to oval shape at HL=50%. The fluid isotherms move and get crowded near the heated section thus indicating increased thermal gradient when heater length is increased from 20% to 50%. The solid isotherms too get distorted and move towards vertical direction from being nearly horizontal when heater length is increased from 20% to 50%.

Fig.3 illurates the effect of increased value of interphase heat transfer coefficient. This figure corresponds to constant values of $Ra = 100, Rd = 1, Ar = 2, Rr = 1, H = 100\ and\ K = 1$. The increase in interphase heat transfer coefficient facilitates the heat transfer between fluid and solid phases of porous medium. Thus the energy level between fluid and solid phases try to reach at same level which is very much demonstrated by fluid and solid isotherms that look very much similar reaching the equilibrium condition. This is consistent with previously reported studies (Saied(2006), Badruddin *et al*, (2007b, 2012b), Ahmed *et al*., 2011). The streamlines magnitude increases with increase in H value thus increasing the fluid velocity turning the secondary circulation into weak form as compared to that of low value of H.

Fig 4 shows the effect of aspect ratio of annulus and the length of heater placed at top section. This figure corresponds to the constant values of $Ra = 100, Rd = 1, Ar = 1, Rr = 1, H = 15\ and\ K = 1$. It is interesting to note that the fluid does not break into secondary circulation as observed in case of Ar=2 (fig 2) rather circulates in one cell for all three cases of heater length. The flow direction also changes when aspect ratio is changed from 2 to 1. It is seen that the larger area of solid phase is occupied by increased temperature when length of the heater is increased as indicated by the solid isotherms of fig 4

Fig.5 shows the average Nusselt number variation with respect to H for heater placed at top section of inner radius with $Ra = 50, Rd = 1, A_r = 2, R_r = 1 and\ K = 100$. The average Nusselt number increases with increase in the heater length which is the result of increased temperature gradient near the heated section as observed in isotherms of fluid and solid (fig 2,3). The fluid Nusselt number remains constant with change in H. The influence of H is higher for the case when HL=50% compared to lower heater lengths. It may be noted that initially, the average Nusselt number of solid decreases and then increases with respect to increase in inter phase heat transfer coefficient (H) when heater is placed at bottom section of annulus but that behavior is not seen when the heater is placed at top section of annulus.

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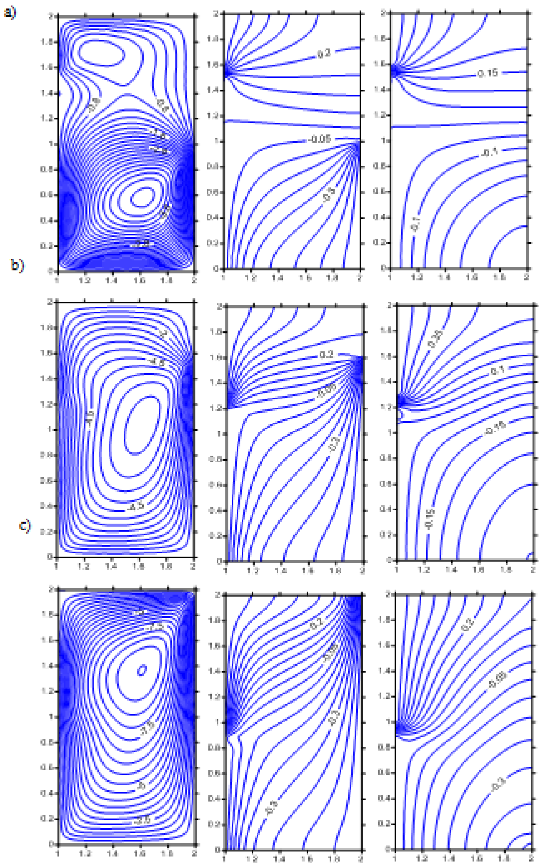

Fig. 2: Streamlines (left) Isotherms for fluid (centre) and solid (right) for heater placed at top section a) HL=20% b) HL=35% c) HL=50% at $Ra = 100, Rd = 1, Ar = 2, Rr = 1, H = 100\ and\ K = 1$.

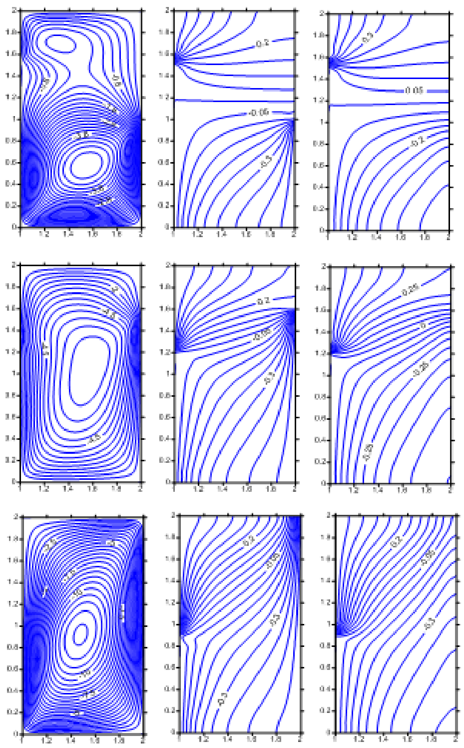

Fig.3: Streamlines (left) Isotherms for fluid (centre) and solid (right) for heater placed at top section a) HL=20% b) HL=35% c) HL=50% at$Ra = 100, Rd = 1, Ar = 2, Rr = 1, H = 100\ and\ K = 1$.

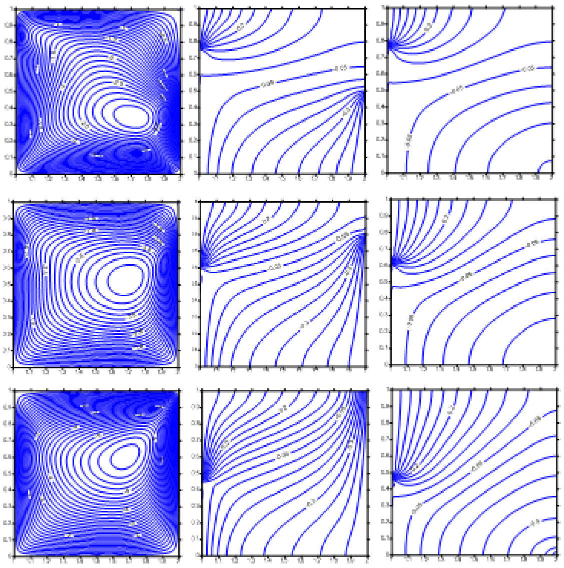

Fig. 4: Streamlines (left) Isotherms for fluid (centre) and solid (right) for heater placed at top section a) HL=20% b) HL=35% c) HL=50% at $Ra = 100, Rd = 1, Ar = 1, Rr = 1, H = 15 \text{ and } K = 1$.

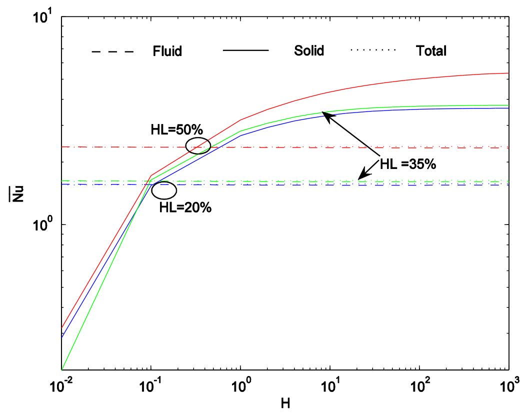

Fig. 6: Average Nusselt number variation with H and different heater length at top section of annulus.

Conclusion:

The present study is carried out to investigate the effect of length of heater placed at top section of an annular porous medium. The study is conducted for three cases of heater length i.e. 20%, 35% and 50% of annulus length. It is seen that the increased length of heater increases the fluid velocity inside the medium. The higher aspect ratio and lower length of heater weakens the fluid flow thus creating secondary circulation field. It is found that the Nusselt number increases with increase in the length of the heater. The heat transfer behavior of top section of annulus being heated is substantially different from that of the case when bottom section of annulus is heated.

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