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Forced Convection Heat Transfer In A Horizontal Pipe Partially Filled With Porous Media - A Finite Element Analysis by using the CBS Procedure.

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ABSTRACT

A finite element analysis using the characteristic based split (CBS) scheme for steady flow in a pipe partially filled with a porous media of diameter 43.5 mm, placed at the core of the pipe in the first case and and in the second case by inserting the porous medium of diameter 72 mm, at the annulus of the pipe for porosity value of 0.46 is carried out. The results are obtained for the initial transient state up to the study state. Identical dimensions and boundary conditions .for pipe flow used in experimental work [1] are considered in geometric modeling. and in numerical analysis..The experimental results are used to verify and validate the numerical model based on characteristic based split method. after ascertaining the correctness of the numerical results, numerical simulation work has been extended to the porosity values of 0.2,0.6 and 0.8 to know the the pressure drop and temperature distribution along the length of the pipe. The pressure drop for porosity values of 0.4 and 0.6 are very close to each other . It shows that there is no much change in pressure drop between the porosity from 0.4 to 0.6. But, the core region porous medium with porosity 0.4 gives higher heat transfer than porosity 0.6, which indicates that the optimum value for porosity lies between these two values.

Key words: characteristic based split method, heat transfer, pressure drop.

Nomenclature			
c	specific heat	v	velocity component in r-direction .
F	inertia coefficient	q	Heat flux
k	Thermal conductivity.		***Greek symbols***
K	permeability	μ	viscosity
m	mass flow rate	ρ	Density.
Nu	Nusselt number		***Subscripts***
p	Pressure.	e	effective
T	Temperature	f	Fluid
u	velocity component in z-direction	i	interface

1. INTRODUCTION

The research in porous medium is a very fascinating field of study as it is inter disciplinary in nature and variety of problems of interest can be addressed in wide range of applications coming under engineering sciences, physics earth sciences and biological sciences. Engineering applications of heat and fluid flow in porous medium range from mechanical, civil, chemical, environmental and nuclear Engineering, to bio engineering. Heat transfer performance of different partially filled porous systems have been studied by a number of authors. Pavel and Mohammad [2] showed that Nusselt number increases through partial filling, while the pressure drop is less than that of a conduit fully filled with a porous medium. Importantly, the configuration of the porous insert in the pipe can have a substantial effect on the rate of heat transfer. Alkam and Al-Nimr [3,4] studied the problem of transient developing forced convective flow in concentric pipes and in circular channels partially filled with porous inserts. They showed the role played by the thickness of the porous medium, the Darcy and Forchheimer numbers, upon the hydrodynamic and thermal system performances. These researchers reported that heat transfer can be enhanced up to 8 times and that the Nusselt number may improve up to 1200 % by the inclusion of a porous substrate. Mohamad [5] numerically investigated the problem of heat transfer enhancement for a laminar flow in a pipe fully or partially filled with porous medium inserted at the core of the conduit. It was shown that with the porous material partially filling in the core of a conduit, the rate of heat transfer from the wall increased with a reasonable pressure drop, and the thermally developing length reduced by 50% or more. This partially filling method works better than the fully filled one.

Pavel and Mohamad [6] studied convection heat transfer of laminar flow in a tube partially or totally filled with porous medium numerically. The porous substrate was inserted at the core. It was shown that in the case of partially filling, heat transfer rate increased while the pressure drop decreased in comparison with fully filled tube. Huang *et.al.* [7] have further investigated the enhanced heat transfer effect of metallic porous materials that are inserted into the core of a pipe with a constant and uniform heat flux experimentally and numerically. The results obtained showed that compared with the clear flow case where no porous materials was used, higher heat transfer rates can be achieved using porous inserts whose Diameters approach the diameter of the pipe and it is very important to get the accurate physical parameters of a porous material from the experiment for a successful numerical simulation. Yang and Hwang [8] numerically investigated the turbulent fluid flow behavior and heat transfer enhancements in a pipe fully or partially filled with porous medium inserted at the core of the conduit. The impact of Re number, Da number and porous radius ratio on heat transfer performance was analyzed in detail.Yang and Hwnag [9] recently investigated the heat transfer enhancement in a tube with a porous core for a broad range of the Reynolds number values(5000 to15000). Moreover, these authors reported that the optimum porous-radius ratio is around 0.8.. It shows that the core flow enhancement is an efficacious method for enhancing heat transfer.

C. Yang *et al.*[10] studied Forced convection in a tube with its core partially filled with a porous medium both analytically and numerically to find its high heat transfer performance. Assuming a fully developed flow subject to a constant heat flux, both friction factor and Nusselt number are presented explicitly as functions of the Reynolds number, Darcy number and porous core diameter ratio. It shows that, there exists the optimal porous core diameter ratio as a function of the Darcy number, which yields the maximum heat transfer coefficient. The characteristic-based split (CBS) method is finite element method for solving the NS equations. This method was proposed by Zienkiewicz and coworkers, first applied to the convection-diffusion equations and then to the NS equations and the CBS method was proved primarily to be effective for both incompressible and compressible flows .Then, this method was further developed and extended by Zienkiewicz and other researchers and its robustness, versatility and accuracy were improved the the application of CBS scheme for flow through porous media are very few (Massarotti et al., [11,12] Salomoni and Schrefler, [13], Arpinoet al., [14], however a very little work has been done using CBS finite element scheme in porous medium field. The aim of this paper is to study forced convection heat transfer in a horizontal pipe partially filled with porous media, to our best knowledge there is no attempt has been made in the literature to solve this type of problem using CBS finite element method.

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2. BASIC EQUATIONS

A schematic diagram of a two dimensional models selected for the problem under consideration are shown in Fig1. The following assumptions are considered in numerical analysis. The porous media model incorporates an empirically determined flow resistance in a region of the model defined as “porous”. Porosity for the porous media model is accounted in governing momentum and energy equations. In general, the porosity is assumed as isotropic for both single phase and multiphase in porous medium model and it can vary with space and time.

The interactions between a porous medium and shock waves are not considered. A local thermal equilibrium (LTE) assumption is assumed to exist between solid and fluid phase when the volumetric heat transfer coefficient is high and there is no heat released in the fluid or solid phase

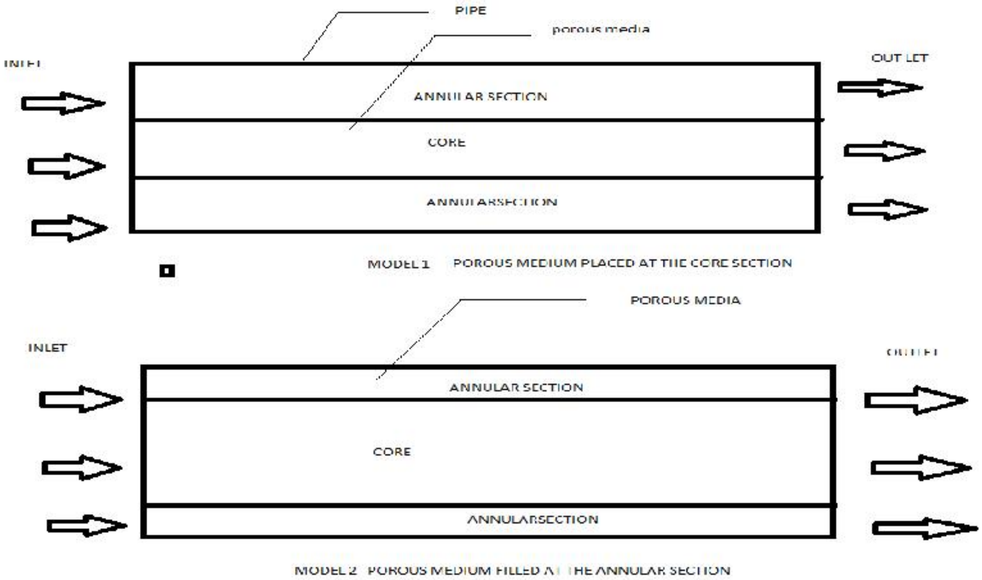

Fig. 1. Geometrical model

In the porous medium viscous drag and inertia terms are considered which are valid assumptions for forced convection
high darcy and particle reynods numbers. With these assumptions, the continuity, momentum and energy governing equations for unsteady two dimensional flow in an isotropic and homogeneous porous medium in cylindrical co-ordinates [16] are

Continuity equation:

$$\frac{\partial}{\partial z}(\rho u) + \frac{1}{r}\frac{\partial}{\partial r}(r\,\rho v) = 0 \quad (1)$$

Momentum equation in Z -direction:

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial z}(\rho uu) + \frac{1}{r}\frac{\partial}{\partial r}(r\,\rho uv) = -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\left(\mu_e \frac{\partial u}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\mu_e \frac{\partial u}{\partial r}\right) - \frac{\mu u}{k} - \frac{\rho F}{\sqrt{k}}u \quad (2)$$

Momentum equation in r –direction:

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial z}(\rho uv) + \frac{1}{r}\frac{\partial}{\partial r}(r\,\rho vv) = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial z}\left(\mu_e \frac{\partial v}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\mu_e \frac{\partial v}{\partial r}\right) - \frac{\mu u}{k} - \frac{\rho F}{\sqrt{k}}v - \frac{\mu v}{r^2} \quad (3)$$

The energy equation while neglecting viscous dissipation effect and heat generation may be written as

$$\frac{\partial}{\partial t}(\rho_e c_e T) + \frac{\partial}{\partial z}(\rho_e c_e uT) + \frac{1}{r}\frac{\partial}{\partial r}(\rho_e c_e r v T) = \frac{\partial}{\partial z}\left(k_e \frac{\delta T}{\delta z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\,k_e \frac{\delta T}{\delta r}\right) \quad (4)$$

3. BOUNDARY CONDITIONS

The specification of boundary conditions is extremely important since it directly affects the stability and accuracy of the solution boundary conditions at Inlet, outlet, top and bottom are set as shown in the Fig 2.and the appropriate expressions are

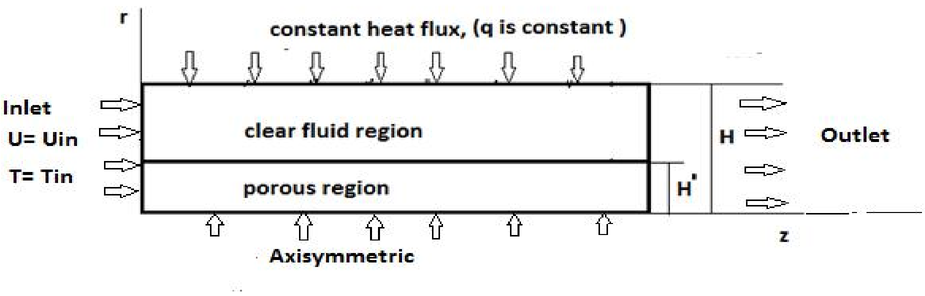

Fig. 2.

Inlet boundary conditions $u = u_{in}$, $v = 0$, $T = T_{in}$ (5)

Outlet boundary conditions $v = 0$, $\frac{\partial u}{\partial z} = 0$, $\frac{\partial T}{\partial z} = 0$ (6)

top boundary conditions $u = v = 0$ (no slip boundary conditions) $q =$ constant (7)

Bottom side boundary conditions.(Axisymmetric) $v = 0$, $\frac{\partial u}{\partial r} = 0$, $\frac{\partial T}{\partial r} = 0$ (8)

4. NUMERICAL METHOD

The above governing equations (1) to (4) in the present problem are solved by using Characteristic Based Split (CBS) finite element method. [15]. A fully implicit scheme is applied for discretizing the time derivatives Characteristic Based Split (CBS) method consists of the following steps.

Step -1: The pressure term from the momentum equations is dropped and an intermediate velocity field is calculated. Step -2: The pressure term is calculated separately by pressure Poisson equation

Step -3: intermediate velocity is corrected using pressure term to get the real velocity of the fluid flow.-4: Temperature field is obtained by solving energy equation using real velocity of the fluid.

The algebraic equations obtained from CBS scheme are expressed in matrix form (9) to (14) are solved for convergence criteria the relative variation of the temperature and pressure between two successive iterations are demanded to be smaller than the previously specified accuracy levels of 10^{-8} .The iterative procedure is initiated by the solution of intermediate velocity field followed by the solution of pressure equation and correcting velocity field and then solving the energy equation

Momentum equation in Z- Direction

$[M_p]\{\Delta\tilde{u}\} = \Delta t\,[-[cp]\{u\}-[kp]\{u\}-[Mp_1]\{u\}-[Mp_2]\{u\}]^n + \{f1\} - [\frac{\partial\rho}{k}]\{u\} - [\frac{\rho F}{\sqrt{K}}]\{u\}$ (9)

Momentum equations in r -direction

$[M_p]\{\Delta\tilde{v}\} = \Delta t\,[-[c_p]\{v\}-[k_p]\{v\}-[Mp_1]\{v\}-[Mp_2]\{v\}]^n + \{f2\} - [\frac{\partial\rho}{k}]\{v\} - [\frac{\rho F}{\sqrt{K}}]\{v\}$ (10)

Equation for pressure field: $[k_p1]\{p\}^{n+1} = -\frac{1}{\Delta t}[[Gp_1]\{\tilde{u}\} + [[Gp_2]\{\tilde{v}\}]n - \{f3\}$ (11)

Equation for Momentum correction

$[Mp]\{\Delta u\} = [Mp]\{\Delta\tilde{u}\} - \Delta t\,[[Gp_1]]\{p\}^{n+1}$ $[Mp]\{\Delta v\} = [Mp]\{\Delta\tilde{v}\} - \Delta t\,[[Gp_2]]\{p\}^{n+1}$ (12)

Equation for Temperature calculation: $[M]\frac{\Delta T}{\Delta t} = -[C]\{T\}^n - [k_t]\{T\}^n - [k_s]\{T\}^n + \{f4\}$ (14)

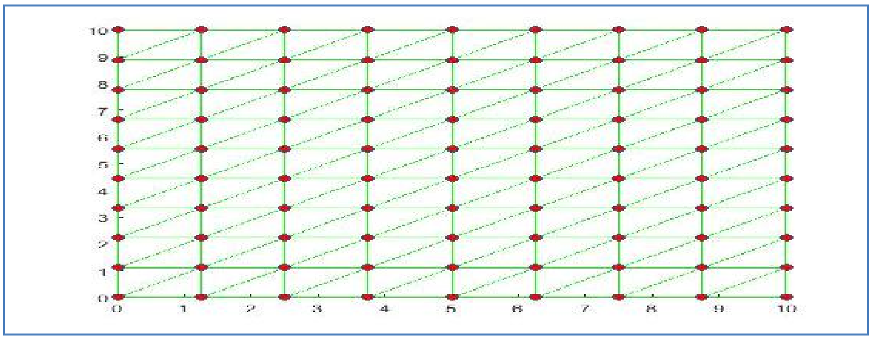

Fig. 3. Typical Mesh for the solution of porous medium problem

A study state problem can be obtained , using the CBS scheme , by time –stepping to achieve a study state. This can be done by fixing the tolerance criterion as follows.

$$\sum_{k=0}^{n} \frac{\phi_i^{n+1} - \phi_i^{n}}{\Delta t} \leq \epsilon \qquad (15)$$

Where ϕ_i is any heat convection at a node, n is the total number of nodes and ϵ is a prescribed tolerance, which will tend to zero as the solution approaches steady state.

5. RESULTS AND DISCUSSIONS

The numerical results are compared with the experimental data for 0.45 porosity and 43.5 mm and 72 mm Core and Annulus diameter of porous media..

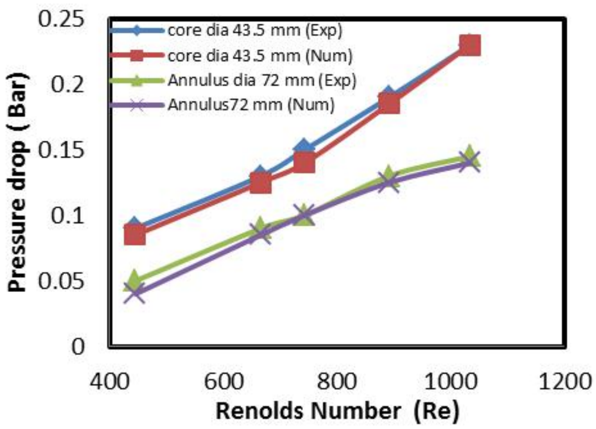

Fig 4. variation of pressure drop against Reynolds number for porosity 0.45

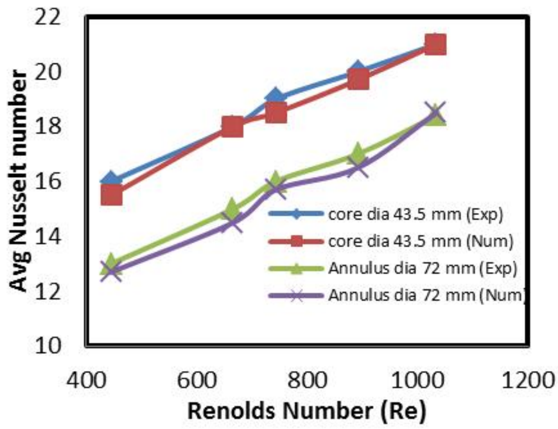

Fig 5. variation of Average Nusselt Number against Reynolds number for porosity 0.45

From the above graphs. It is clearly revealed that the agreement between the Numerical and experimental results are very good indeed. So these results ensure the accuracy of the present numerical work. There is a clear indication that the core section offers more pressure drop in comparison with the annular section due to the presence of the porous medium. The reason for this is attributed to more flow in the center region of the pipe. The core provides a large pressure drop being right in the path of the bulk amount of water flow. On an average, the core offers 1.2 times more pressure drop when compared to the annular section, keeping the porosity constant. From the fig.5, we can primarily infer that the Nusselt number increases with an increase in Reynolds number which is a function of mass flow rate. This is mostly attributed to the fact that the increase in mass flow rate results in more heat being carried away by the water flowing through the pipe. It is evident that in, the porous medium of 0.45 porosity placed at the core of the pipe gives better Nusselt number value.. The reason for this is that the presence of the core in the center region pushes most of the water to flow close to the wall for which a constant heat flux is supplied. An increase in mass flow rate at the open region results in a heat transfer enhancement at the open region.. It is also noticed that the core gives about 20 % more heat transfer when compared to the annular section inserted inside the test section.

5.1 Parametric study

From the experimental and numerical results, it is clearly depicted that the core region gives better heat transfer compared to annulus region. Hence, The parametric study is carried out for core region only, to know the effect of a porosity of the porous medium on heat transfer and pressure drop characteristics, keeping all other parameter constant for core diameter value of 43.5 mm. using porosity values of 0.2, 0.4,0.6 &0.8

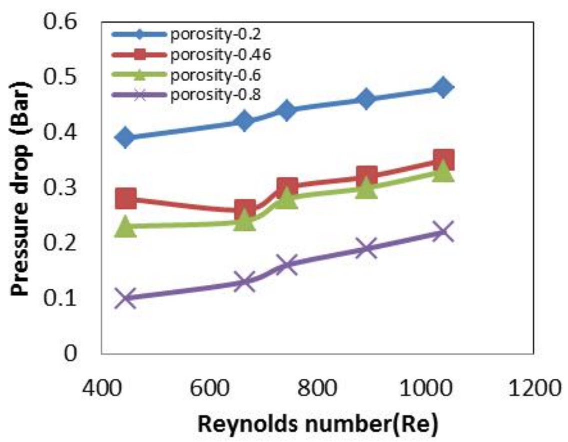

Fig 6. Variation of pressure drop against Reynolds number core diameter 43.5 mm

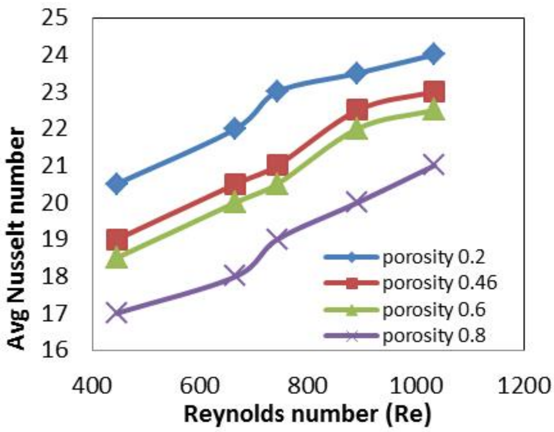

Fig 7. Variation of Average Nusselt number against for Reynolds number for core diameter 43.5 mm.

From the above plots, it is clear that the pressure drop increases with increase of Reynolds number which is a function of mass flow rate and decreases with increase of porosity value for core region. It is because of reduction in viscous friction due to the increase of void space in porous media. But it is also observed that there is reduction in heat transfer too. The closer packed structure requires the water to use more force to pass through the smaller gaps. Hence, there is a larger pressure drop for porous medium of porosity 0.2. The pressure drops for porosity 0.4 and 0.6 are very close to each other. It shows that there is no much change in pressure drop between the porosity from 0.4 to 0.6. But, the core region porous medium with porosity 0.4 gives higher heat transfer than porosity 0.6, which indicates that the optimum value for porosity lies between these two values .

6. CONCLUSIONS

There is a definite increase in heat transfer with the use of porous inserts as compared to clear flow case where no porous materials are used. There is an increase in Nusselt number with Reynolds number. The increase although not proportionate is clearly noticeable. The increase is attributed to an increase in mass flow rate. Nusselt number also increases with effective area of the porous medium. This happens because of larger Eddy disturbances and more turbulence created with a section of larger area. However, this in accompanied with an increase pressure drop. The variation in between two subsequent area of the porous insert is about 20 % .There is a variation in Nusselt number and pressure drop with position of porous insert as well. The core shaped porous insert offers better heat transfer when compared to the annulus shaped porous insert. The increase in heat transfer for same effective area and for same porosity is on an average 30% greater for the core shaped insert when compared to the annulus shaped insert. Consequently, the pressure drop using the core is 1.2 times the pressure drop using the annulus The Nusselt number and pressure drop both increases with a decrease in porosity.

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