CFD Simulation of Flow and Heat Transfer in a Horizontal Pipe Partially Filled with Porous Media

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***Abstract:* - Computational fluid dynamics (CFD) is a numerical technique which solves the governing equations of fluid flow ,heat transfer and other associated equations ,iteratively on discretized complex geometries. The quality of the solutions obtained from these simulations are largely within the acceptable range proving that CFD is an effective tool for predicting the behavior and performance of a wide variety of heat and fluid flow problems. In the present work a finite volume analysis using Ansys fluent for steady flow in a pipe partially filled with a porous media of diameter 49.6 mm placed at the core of the pipe in the first case and in the second case by inserting the porous medium of corresponding diameter, 69 mm at the annulus of the pipe for porosity value of 0.56 is carried out. The results are obtained for 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 The simulation results are within good agreement with the experimental studies ranging from 2% to 10% , 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.**

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

I. INTRODUCTION

The convection heat transfer occurs in different systems such as heat exchangers ,domestic refrigerators, automobiles, electronic devices ,building structures , catalytical bed reactors , packed bed generators ,fixed bed nuclear propulsion systems ,fuel cells , solid matrix heat exchangers and also in rocks and soils. The porous medium approach helps engineers in enhancing convection heat transfer. In all these problems, one will look to effectively reduce the flow resistance and to increase the heat transfer in porous medium and this has received much attention during last two decades Poulikakos and Kazmierczak [2] investigated fully developed forced heat convection in a channel partially filled with a porous medium. They found that the thermal performance of a conventional concentric tube heat exchanger could be improved by inserting high thermal conductivity porous substrates. Vafai and Kim [3] showed that enhancement of heat transfer using porous material depends on the ratio of the effective thermal conductivity of the porous medium to that of the fluid. Hadim [4] performed a comprehensive numerical study of forced convection in a porous channel with heat sources mounted on the bottom wall. The heat transfer enhancement and pressure drop in a partially filled porous channel are calculated and compared with that for fully filled porous channel case.

B.I. Pavel, A.A. Mohammad, [5] 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. Carlos G et al. [6] In their work solved effective-medium equations for modeling momentum and heat transfer in a parallel-plate channel partially filled with a porous insert., it was found that the thermal performance is improved by either increasing the size of the porous insert or by favoring mixing inside the channel. A drawback of this approach is the high computational demand associated to modeling transport in the vicinity of the porous medium and the fluid. Furthermore, previous works have shown that depending on the thickness of the porous material and other pertinent parameters the fluid velocity in the clear region and at the interface changes Alkam and Al-Nimr studied the problem of transient developing forced convective flow in concentric pipes in [7] and in circular channels [8] 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. Alkam and Al-Nimr [9] presented a numerical simulation for the transient forced convection in the developing region of a pipe partially filled with a porous material. The porous matrix is adhered to the inner wall of a pipe which is subjected to a step change in the temperature. They found that the time needed to reach steady state condition increases as the porous thickness increases up to a definite limit and then decreases with further increase in the layer thickness Marafie and Vafai [10] introduced another method by Inserting porous substrates at both sides of the inner tube wall; the thermal performance of a conventional concentric tube heat exchanger can be improved. The improvement was investigated numerically and the results showed that inserting the porous substrate may enhance the effectiveness of the heat exchanger considerably, Liu *et. al.*

[11] developed the new concept of enhanced heat transfer in the core flow along a tube. He proved that the core flow of tubes is worthy to be well used for heat transfer augmentation. The most direct way is to make temperature as uniform as possible in the core flow of the tube in order to form a thin thermal boundary layer near the wall with great temperature gradient, thus resulting in a significant heat transfer enhancement effect.

CFD has emerged as a cost effective alternative and it provides speedy solution to heat and fluid flow problems and optimization Dependability , reliability of CFD results has reached a point making it an integral part of all design processes, leading towards eliminating the need of prototyping Paola Ranut *et* all [12] CFD simulations of flow and heat transfer through three aluminum foam samples have been presented, for all the three samples it shows that at low Reynolds numbers the pressure drop varies linearly with the velocity, at higher Reynolds numbers inertial effects are found to contribute. Vijay Shankar [13] In his study, the heat transfer through a porous region, representing a layer of insulation, with an air cavity above has been numerically investigated with the help of CFD. The magnitude of total rate of heat transfer is dependent on the temperature difference across the domain. The heat transfer due to radiation also plays an important role. Three dimensional computations are recommended in order to obtain an accurate picture of the flow field. Extensive literature study on CFD analysis for heat and fluid flow though porous medium has shown that the basic research conducted so far have only dealt with fully filled porous medium [14-20]. However, during the course of this state of the art research work, an attempt is made to study the forced convection heat transfer in a horizontal pipe partially filled with porous media using Ansys fluent.

II. MATHEMATICAL FORMULATION

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”.

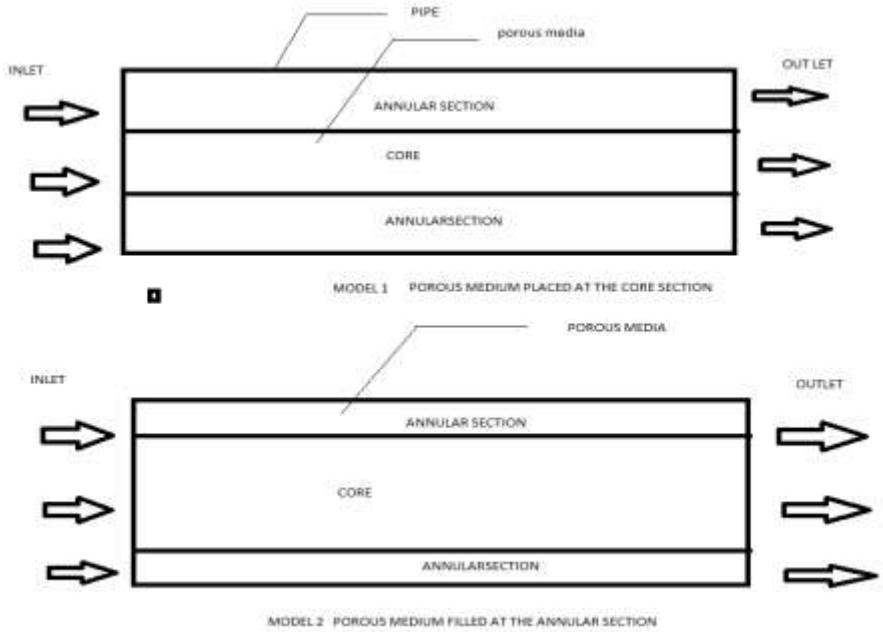


Fig. 1. Geometrical model

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. 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 phaseIn the porous medium viscous drag and inertia terms are considered which are valid assumptions for forced convection high darcy and particle reynods numbers.

III. BOUNDARY CONDITIONS

Inlet boundary conditions are $u = u_{in}$, $v = 0$, $T = T_{in}$ and constant heat flux is set on the wall of the heated flow passage. No slip boundary condition is defined for the wall.

IV. NUMERICAL METHOD

Standard Initialization is the recommended initialization method for porous media simulations The commonly used turbulence model, the $k - \epsilon$ model is applicable to free-shear-layer flows with small pressure gradients. The $k - \omega$ model goes for flows with adverse pressure gradients and separation. Considering the high heat flux and dramatic thermos-physical property variation in the near wall region as well as the low-Re turbulent flow in this work, the SST $k - \omega$ turbulence model is adopted. The buoyancy effect is neglected. The SIMPLEC algorithm with physical velocity concept is adopted. while defining the porous medium viscous (Rv) and inertial resistance (Ri) are calculated by using the following correlations

Rv = [150*(1-e)^2/phi^2*D^2*e^3] -------(1)

Ri = [2*1.75*(1-e)/phi*D*e^3] ------(2)

Where

e: Porosity of the medium . phi: Sphericity of the particles making the medium (can assume 0.75) D: Diameter of particles making the medium

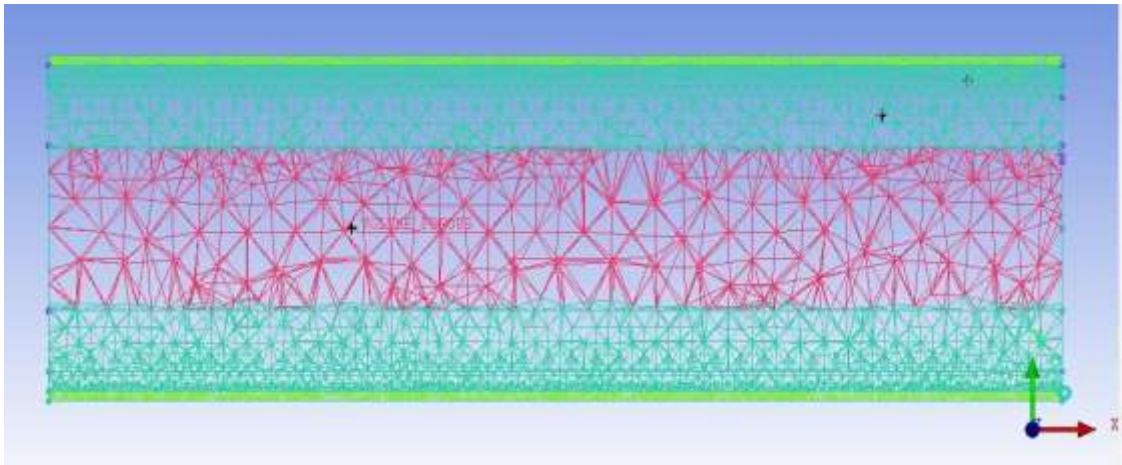
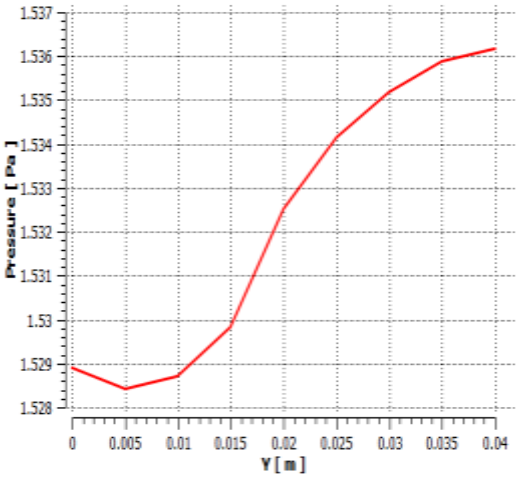


Fig. 2. Mesh generated for porous medium of diameter 49.6 mm inserted at core of the pipe

V. RESULTS AND DISCUSSIONS

Numerical results obtained from CFD simulation are presented for two different cases, where porous media is inserted at the core of the pipe in one case and porous medium is considered in the annulus of the pipe in an another case.

case.1: Porous medium placed at the core of the pipe



case.2: Porous medium placed at the Annulus of the pipe

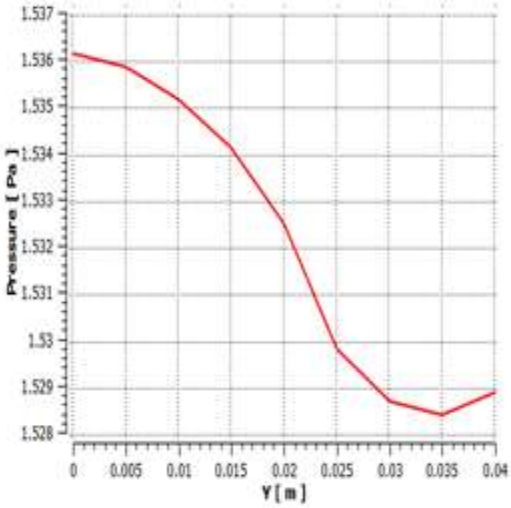


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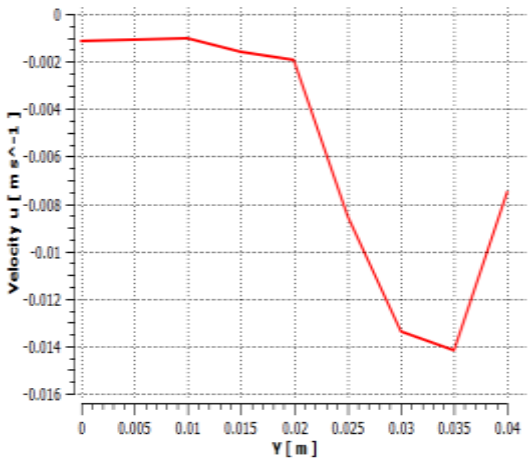
Fig.3. Preessure Vs Radius of the pipe

Fig.4. Preessure Vs Radius of the pipe



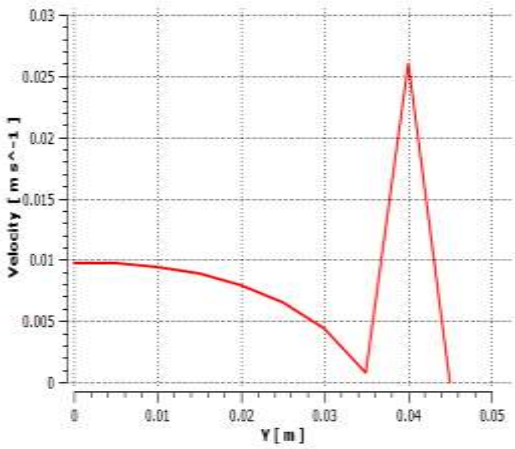
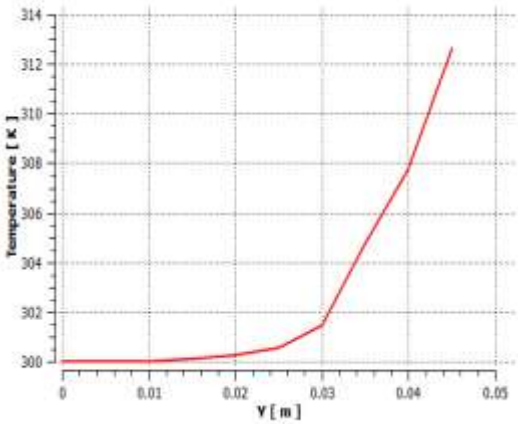


Fig.5. Velocity Vs Radius of the pipe

Fig.6. Velocity Vs Radius of the pipe



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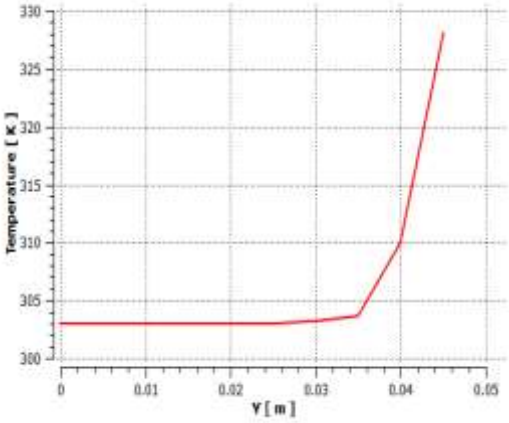
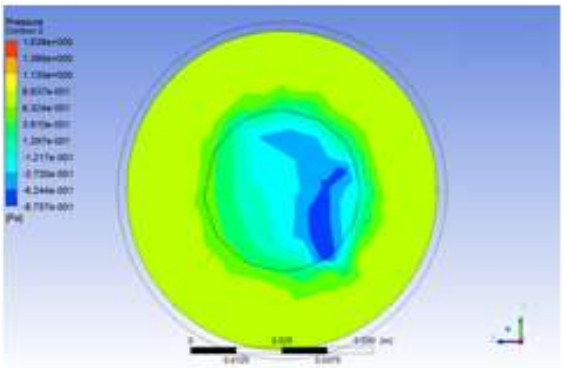


Fig.7.Temperature Vs Radius of the pipe

Fig..8.Temperature Vs Radius of the pipe

case.1: Porous medium placed at the core of the pipe

case.2: Porous medium placed at the Annulus of the pipe



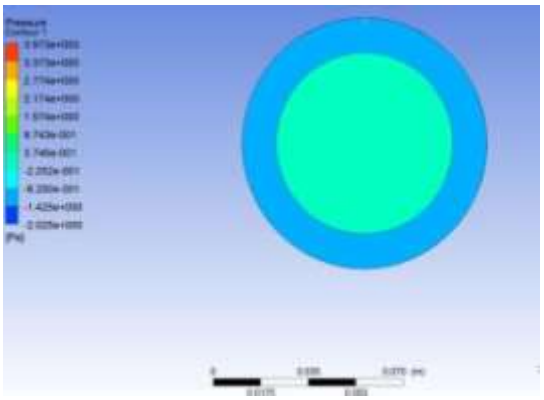


Fig.9. Pressure Distribution

Fig..10. Pressure Distribution

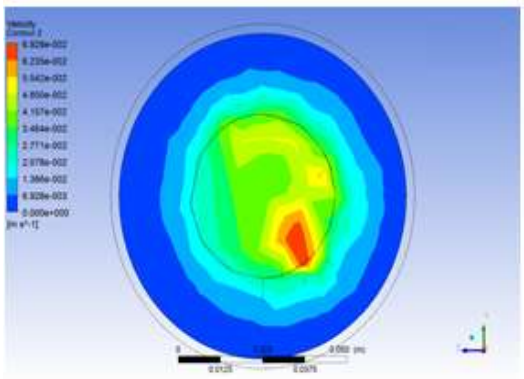


Fig.11. Velocity Distribution

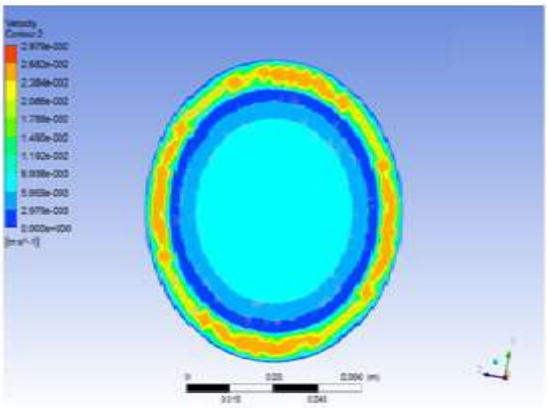


Fig..12. Velocity Distribution

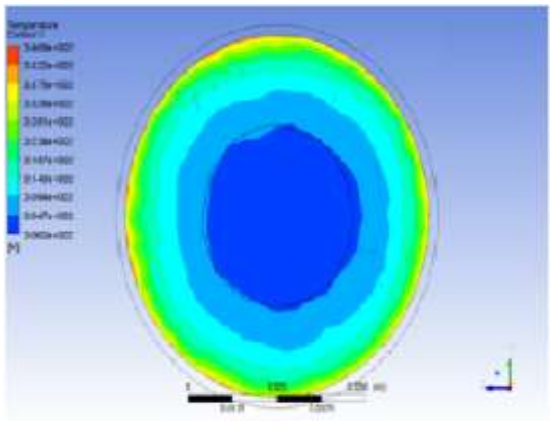


Fig.13. Temperature Distribution

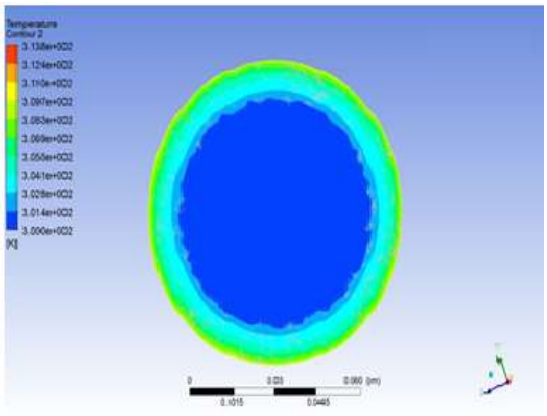


Fig.14.Temperature Distribution

Form the above plots and contours obtained from the Ansys fluent simulation of pipe flow partially filled with Porous media of diameter 49.6 mm and 69 mm placed at the core and annular section respectively., it is clear that there is considerable pressure drop along the porous region and velocity increases rapidly due to this pressure drop. Fig 3and Fig 4 shows the pressure distribution along the radius of the pipe, for case1 and case 2 respectively. It can be observed that there is a decrease in pressure of the fluid at the core when the fluid flows through porous medium. Fig 5 and Fig.6 shows the velocity distribution along the radius of the pipe, for core and Annulus region respectively. From this it is clear that the pressure drop of the fluid when it is flowing through the porous medium is converted in to kinetic energy which increases the velocity of the fluid flowing through the porous medium. The pressure and velocity contours shown in Fig 9,10,11 and 12 justify the same. The temperature distribution along the radius of the pipe for core and Annulus region is displayed in Fig 7 and Fig 8. In the later case there is a high temperature distribution along the fluid saturated porous medium since the porous medium is in direct contact with the hot wall of the pipe. In this case heat energy to the porous medium flows by conduction as well as convection.Where as the heat flow to the liquid saturated porous medium placed at the core is low as it is away from the heated wall and heat transfer is only through convection so there is a low temperature distribution in the fluid flowing through the core section of the pipe. Temperature contours shown in Fig 13 and Fig14 justify the same.

5.a. Numerical model validation

. The numerical results of pressure drop and Nusselt number against Reynolds number are compared with the experimental data for core and annulus diameter of porous media. 49.6 mm and 69 mm respectively for porosity value 0.56

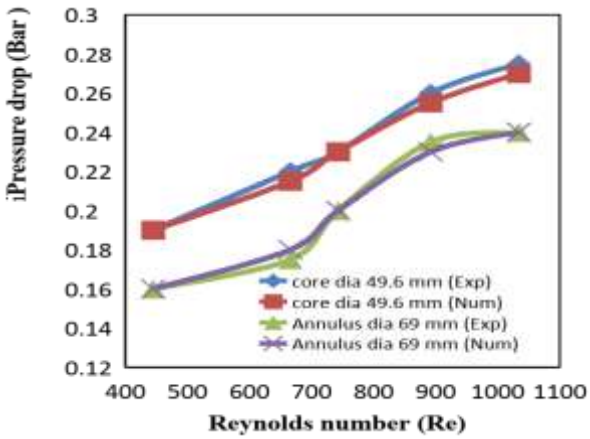


Fig 15. Variation of pressure drop against Reynolds number for porosity 0.56

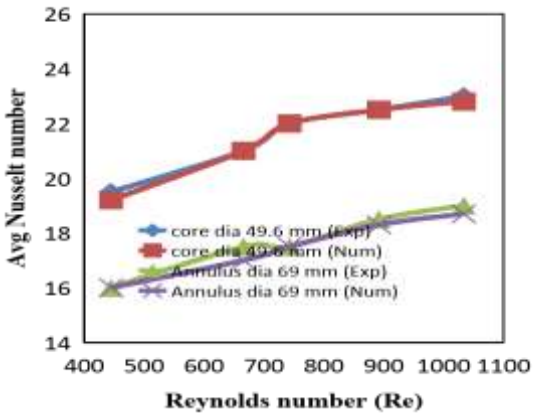


Fig 16. Variation of Average Nusselt Number against number for porosity 0.56

The above graphs show the variation of pressure drop and Nussult number against Reynolds number. The simulation results are within good agreement with the experimental studies ranging from 2% to 10% while in some exceptional cases, vary up to 15%. In case of large deviations, 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 1.5 times more pressure drop when compared to the annular section, keeping the porosity constant.

From the Fig 16, 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.. As the area of the flow decreases, the velocity increases to keep the discharge of water a constant. The increased velocity coupled with eddy current results in local disturbances and increased turbulence. This consequently leads in a higher amount of heat exchanged through convection and hence a higher Nusselt number. . 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.b. 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 particular parameter on heat transfer and pressure drop characteristics, keeping all other parameter constant. Two parameter of interest namely porosity of the porous medium and core diameter. four porosity values of 0.2, 0.4,0.6 &0.8 and core diameter values of 49.6mm & 55 mm are considered in this parametric study results obtained from parametric studies are shown below

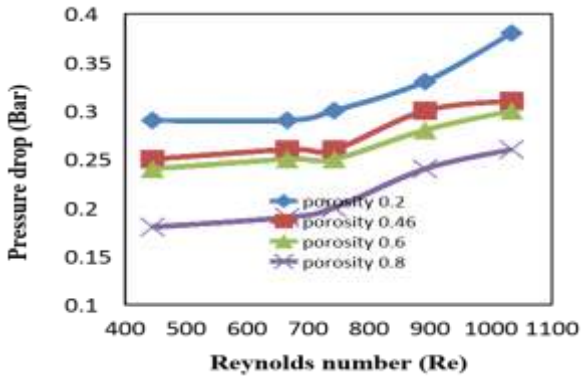


Fig.17. Variation of pressure drop against Reynolds number for core dimeter 49.6 mm

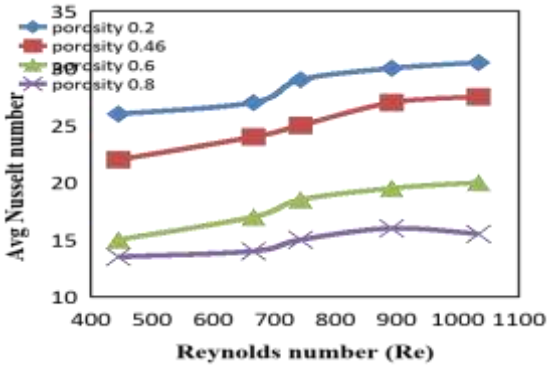


Fig 18. Variation of Average Nusselt number against Reynolds number for core diameter 49.6 mm

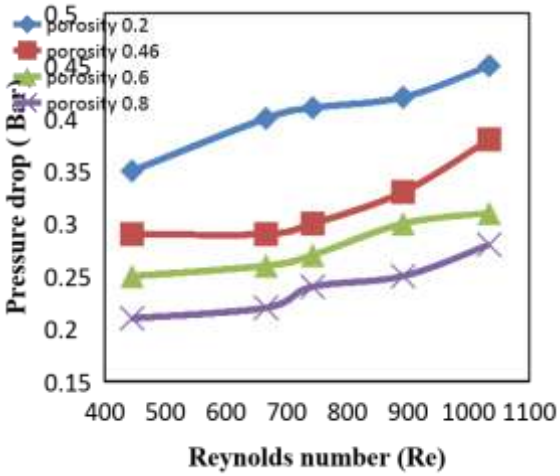


Fig.19. Variation of pressure drop against Reynolds number for core diameter 55 mm

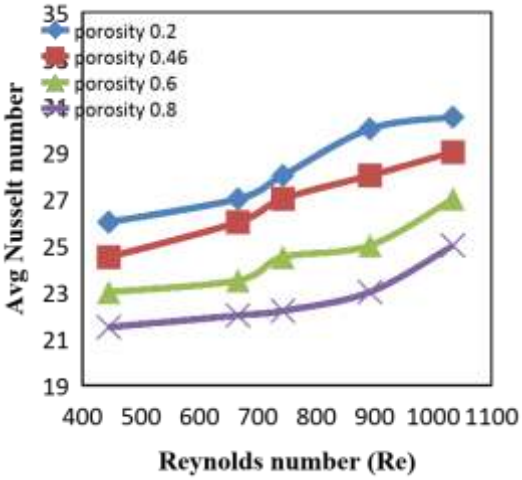


Fig.20. Variation of Average Nusselt number against Reynolds number for core diameter 55 mm

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.

VI. CONCLUSIONS

Heat and fluid flow through a horizontal pipe subjected to constant heat flux boundary condition partially filled with porous medium is considered in this paper, the numerical simulation is carried out by using ansys fluent. it is observed that simulation results are within good agreement with the experimental studies ranging from 2% to 10% . l. It is also observed that 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 25% 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. It is also observed that the pressure drop for porosity values of 0.4 and 0.6 are very close to each other in all the cases. 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.

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