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A Numerical Study On Improving Heat Transfer By Using Porous Inserts In Forced Convection System

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Abstract

Use of porous inserts in a forced convection system is an effective technique for improving heat transfer and so it has a wide range of engineering applications like heat exchangers, nuclear reactors and fuel cells. The effects of porosity, thermal conductivity and Reynolds number on pressure drop and heat transfer rate when water is passed through a pipe fitted with porous inserts and subjected to constant heat flux are studied and compared with the clear flow case without porous material. The permeability, form coefficient and thermal dispersion coefficients are found out numerically and are validated.

Index Terms - Porous Media, Thermal Dispersion, Permeability

Nomenclature

K Permeability of porous matrix [m^2]
v Darcean velocity of fluid [ms^(-1)]
k Thermal conductivity of fluid [Wm^(-1) k^(-1)]
T Temperature at any point in test section [k]
T_"in " Water temperature at the inlet of test section [k]
C_F Form Coefficient
ρ Density of fluid [kgm^(-3)]
v Transverse velocity [ms^(-1)]
c Specfic heat capacity of water [Jkg^(-1) k^(-1)]
r Radial distance from the pipe centre [m]

Introduction

Use of porous inserts in a forced convection system is an effective technique for improving heat transfer and so it has a wide range of engineering applications. The employment of different types of porous materials in forced convection heat transfer has been extensively studied due to the wide range of potential engineering applications such as electronic cooling, drying processes, solid matrix heat exchangers, heat pipe, nuclear reactors, enhanced recovery of petroleum reservoirs, etc. Porous medium finds applications in nuclear reactors where heavy water flows through Uranium fuel rods. Heavy water (D_2O) acts as the coolant which extracts heat from the Uranium fuel rods which act as the porous medium. The porous medium effect enhances the cooling of nuclear reactors. Use of porous materials enhances the heat transfer due to (i) flow redistribution (ii) thermal conductivity modification and (iii) enhancement of radiative heat transfer and so finds applications in heat exchangers. Representative Elementary Volume is the smallest differential volume that results in statistically meaningful local average properties such as porosity, saturation and capillary pressure and that incremental addition of extra pores doesn't change the magnitude of these properties. It is an intermediate volume much greater than pore volume but much lesser than the volume of the entire solid matrix; it is needed when the global length or system dimension of porous medium much greater than pore diameter. A continuum model for a porous medium is based on this concept.

Based on Darcy-Brinkman-Forchheimer flow model, M. U. Uwaezuoke [1] analyzed the viscous dissipation effect on the forced, fully developed convection heat transfer in the flat channel filled with saturated porous medium of power-law fluid. Moreover, it derived the dimensionless calculation formulas for the axial velocity distribution and temperature distribution. Then the dimensionless formulas were numerically simulated by using classical Runge-Kutta method under constant heat flux boundary condition. Alkam and Al-Nimr [2] numerically investigated the thermal performance of a conventional concentric tube heat exchanger and showed that porous substrates of optimum thicknesses yield the maximum improvement in performance. A.A Mohamad [3] investigated the heat transfer enhancement for flow in a pipe or channel partially or fully filled with porous material provided at the core of the channel and concluded that partially filling the channel with porous substrates can reduce thermal entrance length by 50 % and increase the rate of heat transfer from the walls. He stated that the convective heat transfer coefficient is higher for systems filled with porous material than the systems without porous material due to the high thermal conductivity of the porous matrix. Bader Alazmi and Kambiz Vafai [4] conducted a numerical study on aspects of variable porosity, thermal Dispersion, and local thermal non- equilibrium on free surface flows through porous media. They explored the characteristics of momentum and energy transport for free surface flows through porous media is explored in this study. Bogdan I. Pavel [5] conducted an experimental and numerical study on heat transfer enhancement for gas heat exchangers fitted with porous media. He varied the diameter and thermal conductivity of porous inserts manufactured from commercial aluminum screen. It was found that the trans fer enhancement can be achieved using porous inserts whose diameters approach the diameter of the pipe. A. Testu et al [6] conducted an experimental and analytical method for finding thermal dispersion coefficients using a one-temperature model which is based on the notion of an average enthalpic temperature and the solution of an energy equation of the convection-diffusion type. They varied Reynolds number from 12 to 130 and also the Peclet number for water or air flow through a bed of glass beads and estimated thermal dispersion coefficients through an analytical solution of one temperature model. The present work is aimed to conduct a numerical investigation to study thermal dispersion effects, that is, to study the effects of porosity, thermal conductivity and Peclet number on the pressure drop and heat transfer rate when hot water flows through a porous medium consisting of solid matrix with interconnected void. In this problem, hot water flows through a brass rug which consists of 5 sections joined together by flanges and screws. The test section is filled with carbon steel balls and wound round by nichrome wire which is heated at the outer section by an external A.C power supply. The test section is thermally insulated from other sections by Teflon gasket. The work is aimed to evaluate i) permeability (ii) form coefficient and (iii) the effective thermal dispersion coefficients when the porous inserts are used.

Methodology

A numerical model has been developed for the problem defined. The numerical procedure comprises of a three dimensional computational model. Numerical modeling and analysis of the problem was done by using commercially available computational fluid dynamics software's GAMBIT 2.4 and FLUENT 6.3. The whole procedure of the work can be summarized as follows:

a) Numerical Analysis (3D)
b) Modeling - GAMBIT 2.4
c) Analysis - FLUENT 6.3

Numerical modeling

Governing equations:
(i) Continuity Equation:

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

Equation (1) implies that total mass flux in Z and r -directions is constant. First term means total mass flux in Z direction and second term implies total mass flux in r direction.

(ii) z-momentum Equation:

$$\frac{\partial}{\partial z}(\rho uu)+\frac{1}{r}\frac{\partial}{\partial r}(\rho vu)= -\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left(\mu_e\frac{\partial u}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_e\frac{\partial u}{\partial r}\right)-f\left(\frac{\mu u}{k}\right)-f\left(\frac{\rho C_F}{\sqrt{k}}\right)|u|u \qquad (2)$$

Equation (2) implies that total momentum in Z direction is constant. Left hand side indicates the momentum forces in Z-direction while the right hand side specifies the viscous and pressure forces in Z direction.

(iii) r-momentum Equation:

$$\frac{\partial}{\partial z}(\rho uv)+\frac{1}{r}\frac{\partial}{\partial r}(\rho vv)= -\frac{\partial p}{\partial r}+\frac{\partial}{\partial z}\left(r\mu_e\frac{\partial u}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_e\frac{\partial v}{\partial r}\right)-f\left(\frac{\mu v}{k}\right)-f\left(\frac{\rho C_F}{\sqrt{K}}\right)|u|v-\frac{\mu v}{r^2} \qquad (3)$$

Equation (3) implies that total momentum in r direction is constant. Left hand side indicates the momentum forces in r - direction while the right hand side specifies the viscous and pressure forces in r direction.

(iv) Energy Equation:

$$\frac{\partial}{\partial z}(\rho c u T)+\frac{1}{r}\frac{\partial}{\partial r}(\rho c r v T)=\frac{\partial}{\partial z}\left(k_e\frac{\partial T}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r k_e\frac{\partial T}{\partial r}\right) \qquad (4)$$

Equation (4) implies that total energy is conserved. Left hand side indicates the energy stored in Z and r directions respectively while the right hand side specifies the thermal energy change in Z and r directions. The parameter f is set to 1 for flow in a porous medium and zero for clear flow region..

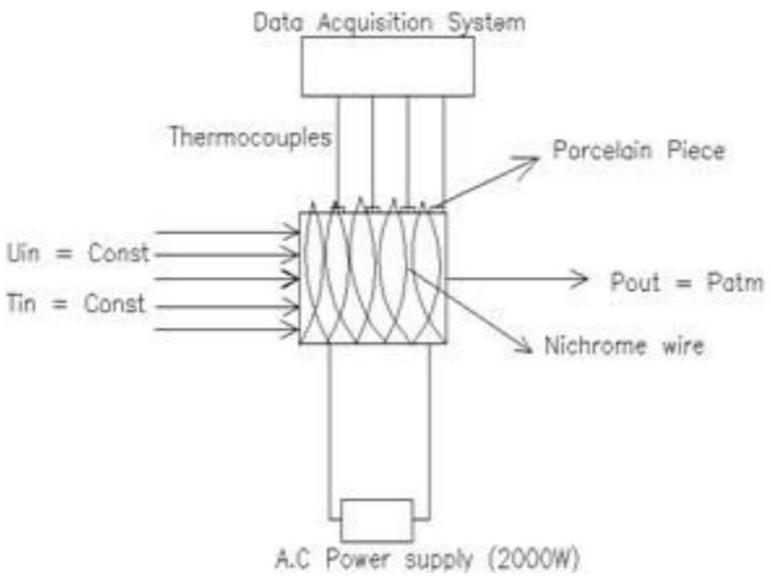

Fig. 1 shows the schematic diagram of the test section which is considered for numerical simulation. Test section is 250 mm long and is filled with steel balls. The steel balls together with the voids between them act as porous medium. The water enters the test section of brass pipe at ambient temperature and is heated by A.C supply through Nichrome wire which is the heating coil. 20 thermocouples are provided at various points of test section to measure the temperature variation along the test section.

Numerical simulation

The boundary conditions for numerical simulation are:

(i) Inlet temperature of fluid is atmospheric temperature.

(ii) The test section is heated by constant heat flux by an A.C supply 2000 W .

(iii) The outlet pressure of fluid is ambient temperature.

The inlet velocity of water is varied. Thus numerical simulation is done for different mass flow rates.

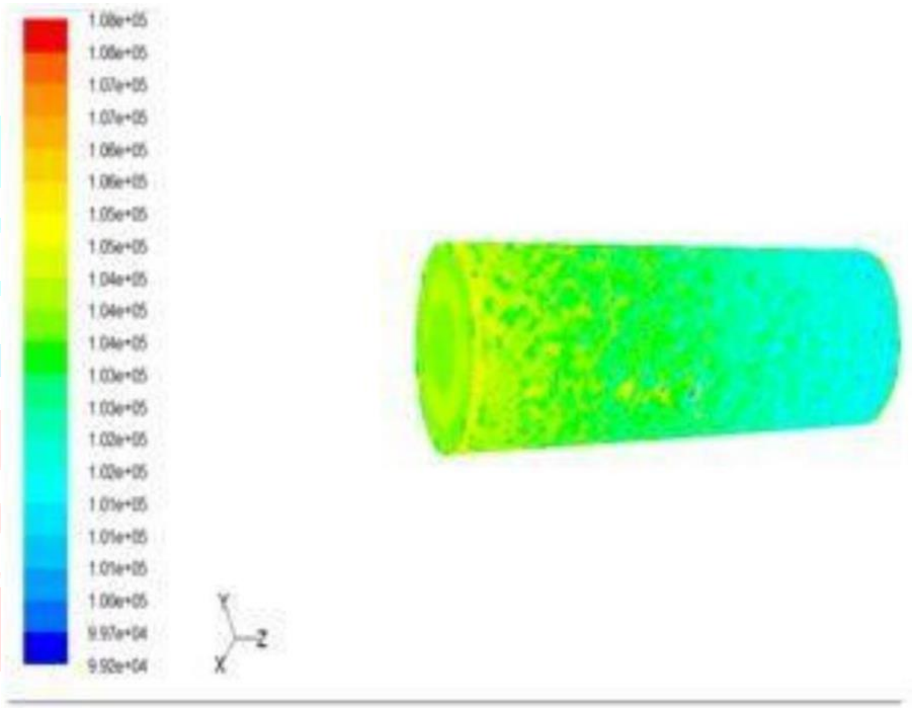

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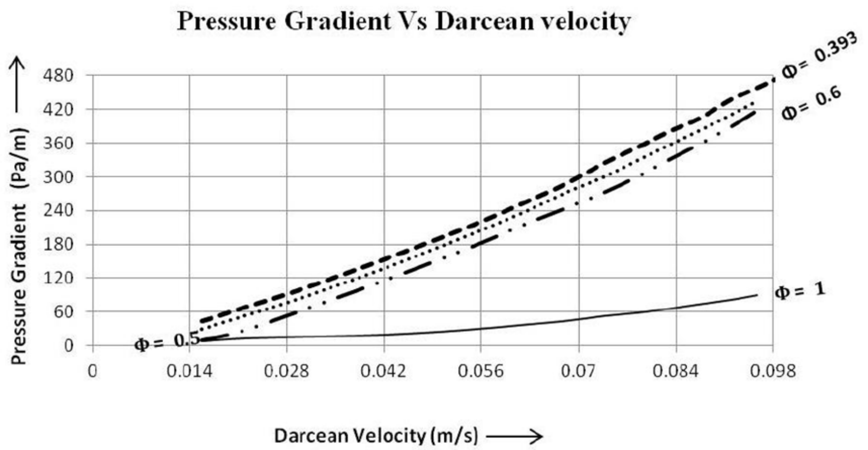
Fig. 2. Pressure variation along the axis of test section

Fig. 2 shows the variation of pressure along the axis of test section. Pressure reduces along the axial direction due to the presence of steel balls in the test section.



From Fig. 3, it is observed that the slope of the curve is maximum for the case with the lowest porosity and minimum without porous medium. The permeability of the porous matrix increases with the porosity as the pressure gradient, which is inversely proportional to permeability, decreases with increased porosity. Fig. 4 shows the variation of dimensionless pressure along the axis of test section. From the figure, it is observed that: . i) Pressure decreases along the axis of test section (ii).Pressure drop intensity increases with decreasing porosity.

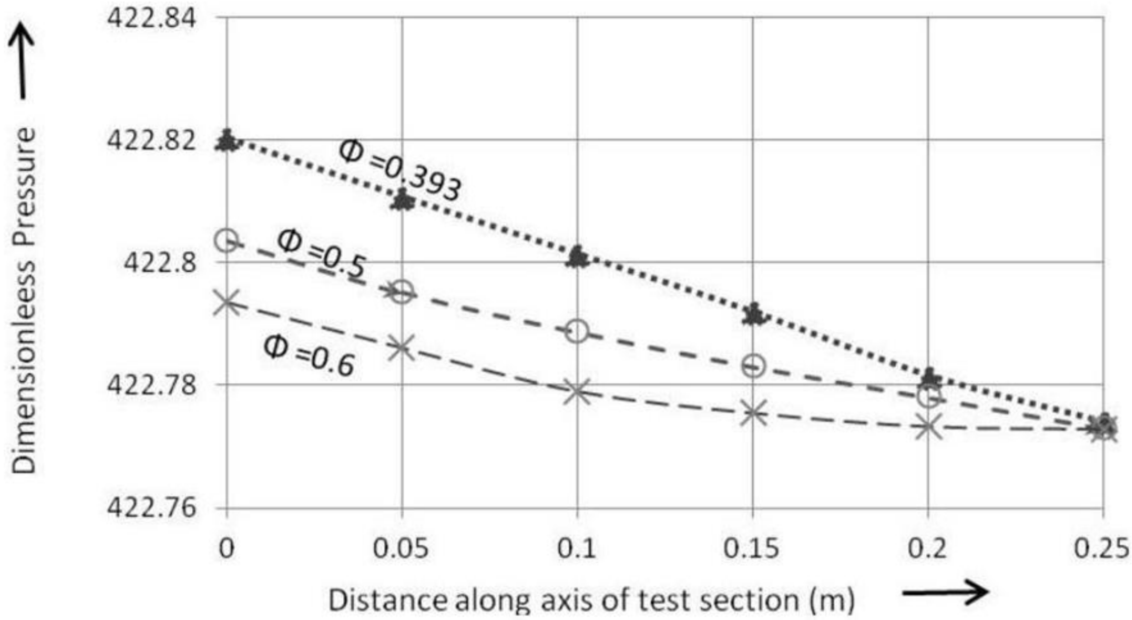


Fig. 4. Dimensionless pressure variation along the axis of test section

Fig. 4 shows the variation of dimensionless pressure along the axis of test section. From the figure, it is observed that: i) Pressure decreases along the axis of test section (ii).Pressure drop intensity increases with decreasing porosity.

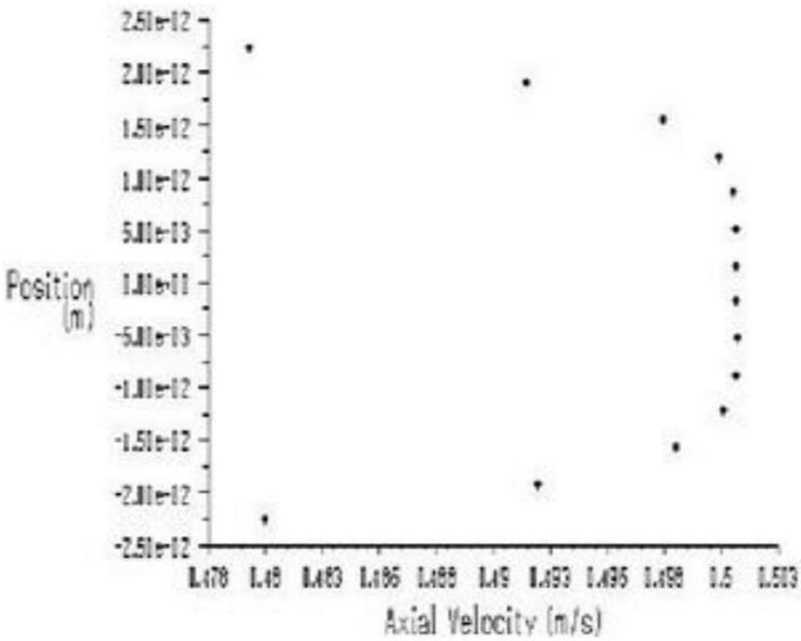


Fig.5. Axial velocity variation along transverse axis

Fig. 5 shows the variation of axial velocity along transverse axis normal to fluid flow. From the figure, it is observed that velocity profile is laminar for porous medium and follows Hagen Poiseullie distribution.

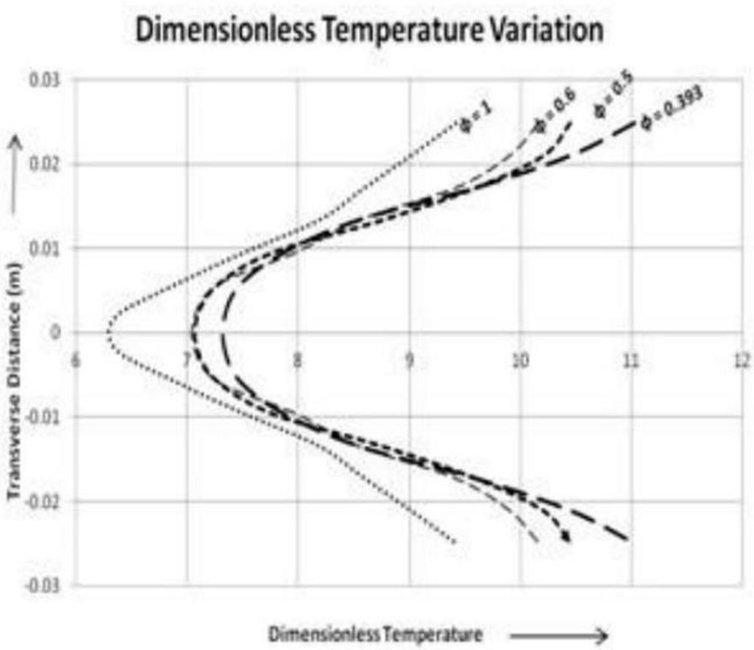


Fig.6. Dimensionless temperature variation along transverse axis

From the Fig. 6, it is observed that (i) temperature is maximum at the extreme position and minimum at the centre. (ii) The temperature is maximum in the case of porous medium with minimum porosity and minimum in the case of clear flow.

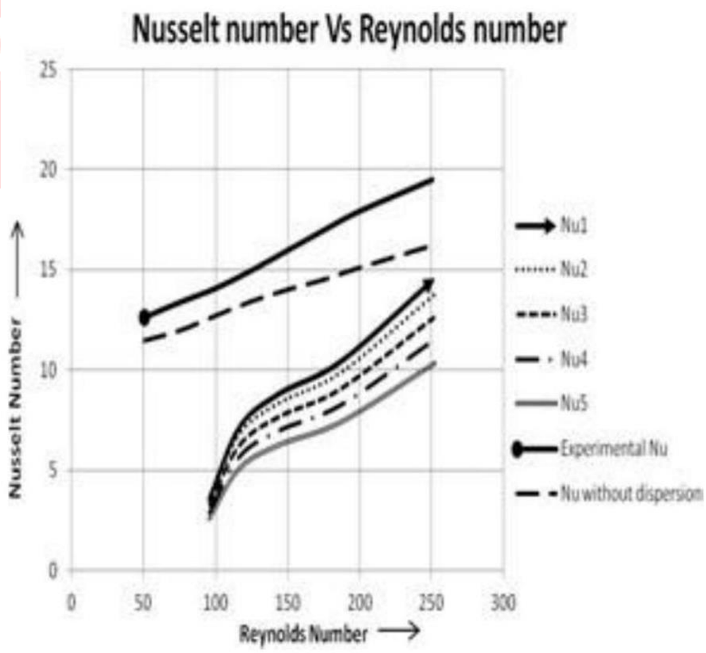


Fig. 7 shows the variation of Nusselt number with Reynolds number. Nusselt number is varied by varying the particle diameter while Reynolds number is varied by varying the average fluid velocity. From the figure, it is observed that Nusselt number which varies for different particle diameter increases with

Reynolds number or flow velocity. The Nusselt number for various steel ball diameters are plotted against various Reynolds numbers and validated against the experimental result from a reference journal.

Conclusions

Present numerical study investigates the potential of porous inserts to enhance the rate of heat transfer occurring between the surfaces of a pipe heated with a constant and uniform heat flux and the water flowing inside it. Some of the conclusions from the numerical study of thermal dispersion in porous media are: (1) The permeability increases with the porosity as the s lope of the Pressure gradient - Darcean velocity graph decreases with increase in porosity. (2) The form coefficient for an experimental porosity of 0.393 was found to be approximately 0.1 in the case of numerical simulation and found to be 0.22 by empirical relation. (3) Axial temperature variation along the transverse axis increases with increase in porosity and is minimum in the case of clear fluid. (4) The velocity profile of fluid flow along axial direction is laminar for flow through porous medium. Axial velocity along transverse axis of test section follows Hagen-Poiseulle distribution. (5) The dimensionless pressure reduces along the axial direction of test section indicating the pressure reduces due to porous medium. (6) The dimensionless temperature reduces in the transverse direction from outer boundary to centre as temperature is higher near the outer heater coil. The main mechanisms identified to be the basis for the heat transfer enhancement when using porous materials are as follows: flow redistribution (flow channeling), thermal conductivity modification, and enhancement of the radiative heat transfer. An experiment is proposed to be conducted in the future to study the effects of thermal dispersion in porous media and how heat transfer is enhanced by it.

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