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**FORCED CONVECTION IN A PIPE FILLED WITH
POROUS MEDIUM**

S Ashok Kumar, M R Rajkumar

College of Engineering, Trivandrum, Kerala, 695016, India

College of Engineering, Trivandrum, Kerala, 695016, India

ABSTRACT

Experiments have been conducted to study flow and heat transfer characteristics in a pipe, filled with porous medium under constant heat flux condition. The porous in-serts used in this study is made of packed steel balls and the working fluid is water. The study have been performed for wide range of Reynold number (5-21) so as to cover the regimes in which Darcian law is applicable. The influence of Reynolds number on the flow and heat transfer charac-teristics of the pipe filled with porous medium is explored and discussed. A correlation for velocity as a function of pressure drop is also developed.

NOMENCLATURE

D Diameter of the Pipe, mm

k_s Thermal conductivity of solid, W/mK

k_f Thermal conductivity of fluid, W/mK

k_d Dispersion Thermal conductivity, W/mK

k_{eff} effective thermal conductivity of stagnant fluid,

W/mK

L Length of the Test Section, mm

P Pressure Drop, Pa

Q Heat Input, W

Address all correspondence to this author.

V_{avg} average fluid velocity, m/s ρ Density of water, kg/m^3

ν Kinematic Viscosity, m^2/s

$$\begin{aligned} \varepsilon & \text{ Porosity} \\ \alpha_f & \text{ thermal diffusivity of fluid, m}^2/\text{s} \\ \text{Re} & \text{ Reynolds Number, } \frac{v_D^{\text{avg}}}{v_f} \\ \text{Pe} & \text{ Peclet number, } \frac{v_D^{\text{avg}}}{\alpha_f} \end{aligned}$$

1. INTRODUCTION

Modern electronic application devices are subjected to high heat flux. Therefore, it is of utmost importance to enhance heat transfer in the cooling channels used for cooling critical components in these devices. The heat transfer in the cooling channels can be increased either by reducing the cooling channel width (micro channel) or by providing porous inserts in the channel. Extensive study by many researchers have shown that introducing porous inserts in cooling channels can drastically improve their heat transfer performances.

Renken and Poulikakos [1] conducted experiments and performed numerical simulations to study the forced convection heat transfer in a parallel plate channel filled with spheres, with channel walls maintained at constant temperature. The results of the study was used to test an existing theoretical model accounting for the effects of macroscopic shear, flow inertia and variable porosity. However theoretical temperature field developed is slower than experimental temperature field due to thermal dispersion. The study also revealed that there is significant increase in local heat transfer at the channel walls compared to that predicted from the Darcy flow model in porous medium. Numerical investigations were performed by Sozen and Kuzay [2] to understand the flow and heat transfer in round tubes filled with copper mesh. The tubes were subjected to uniform heat flux and water was used as the working fluid. They reported that even though high heat transfer could be achieved by using porous inserts the pressure drop in the channel was very high. The authors suggested that one method to overcome this large pressure drop was to use brush type porous inserts consisting of pins fixed on an axial rod at right angles. Experimental investigations were performed by Jiang et al. [3] to study the flow and forced convection in a channel filled with glass, stainless steel or bronze spherical particles with water as the working fluid. The important parameters considered in their work were particle diameter, particle thermal conductivity and fluid velocity. The results of the study revealed that as the particle size decreased the pressure drop increased significantly. It was also reported that for porous plate channel filled with glass particles heat transfer coefficient increased with increasing particle diameter, however when filled with bronze particles heat transfer coefficient increased with decreasing particle diameter. The study also brought out increasing the particle thermal conductivity increased the heat transfer coefficient. Forced convection in a saturated porous medium made of glass beads, heated by a permeable wall perpendicular to flow direction was investigated analytically and experimentally by Zhao and Song [4]. They reported that there is major increase in heat transfer if the flow direction is parallel to the applied temperature gradient. Also at low Peclet numbers the experimental and numerical results compared well. Heat transfer and pressure drop in a rectangular channel with sintered porous inserts, made of stainless steel of different porosity was investigated experimentally by Hetsroni et al. [5]. The study reported that for mini devices having high flux, high heat transfer rates can be attained by using sintered porous heat compared to that of aluminum compressed forms, but at the expense of high pumping power. Hajipour and Dehkrodi [6] performed numerical investigations to analyse mixed convection heat transfer in vertical channel partially filled with porous medium. The study reported that presence of nano particles base fluid can cause noticeable increase in velocity and temperature particularly at high heat fluxes.

The above literature survey reveals that many of the previous investigators have analysed both

experimentally and numerically the effect of particle size, thermal conductivity, type of fluid, and flow velocity on flow and heat transfer in channels filled with porous medium. However the experimental investigation of forced convection in horizontal channels filled with porous medium are scarce. In addition to that effect of particle size, thermal conductivity and fluid velocity on the heat transfer characteristics in channels filled with porous medium needs further investigation to optimize heat transfer from such channels. The aim of this work is to investigate experimentally the effect of fluid flow and heat transfer characteristics in pipe filled with porous steel balls.

2. EXPERIMENTAL SETUP

The schematic of the experimental setup (Fig. 1) consists of a brass pipe of inner diameter 72.8 mm provided with porous medium at the test section. Regulated water flow rate is maintained through the pipe using 0.5 HP pump. Water from the pump passes through a filter, where dirt and other particles are removed, and then passes through a valve where the flow rate is regulated and enters the settling region which is 760 mm in length. After passing through the settling region, enters a 120 mm long pipe (straightener) where small brass tubes of 6.35 mm diameter are placed so as to remove eddies and to provide axially uniform flow. The water coming out of straightener is allowed to pass through a developing region 260 mm in length and finally into the test section. The test section of the pipe is made of brass, 72.8 mm in inner diameter and 250 mm in length ($L=250$ mm) filled with steel balls of diameter 6.35 mm. The outer surface of the test section is wound with nichrome wire, so as to maintain uniform heat flux over the test section. The outer surface of the heater wire is provided with insulations to reduce the heat loss to the atmosphere. K type thermocouples (12 nos) are placed such that 3 Nos are in radial direction across the flow. This is repeated at four longitudinal sections (along X-direction). All the thermocouples are calibrated (see Fig. 2) before they are placed at the respective

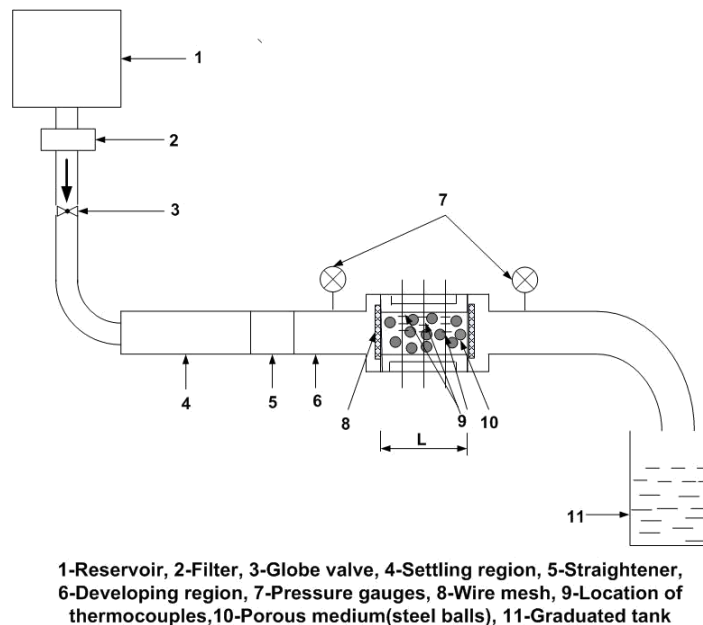


FIGURE 1. SCHEMATIC OF THE EXPERIMENTAL SETUP.

thermocouples are connected to a PC based data acquisition system (KEITHELY-India Ltd). The power input to the heater is given by a regulated DC power supply system (APLAB-India Ltd) having a range of

30-600 V and 0-1.5 A. In order to measure the pressure drop across the test section pressure gauges are provided at the inlet and exit of the test section. The photographic view of the experimental setup is shown in Fig. 3.

2.1 Experimental uncertainty

Experimental results are always uncertain due to the errors involved while measuring independent parameters. The errors in the independent parameters will definitely affect the dependent parameters. Therefore it is very important to estimate the uncertainty in the dependent parameters and this is done by using the procedure outlined in [7]. The estimated values of the uncertainty of various parameters reported in Table.1 show that uncertainty in the values of all the calculated parameters are within the permissible range of $\pm 10\%$.

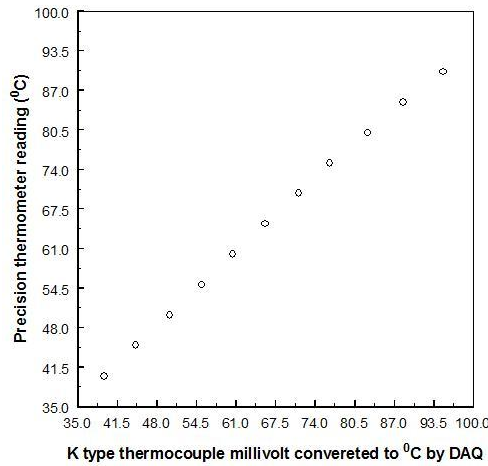


FIGURE 2. CALIBRATION CURVE FOR K TYPE THERMOCOUPLE.



FIGURE 3. PHOTOGRAPH OF THE EXPERIMENTAL SETUP.

2.2 Theory

The flow is assumed to be steady and incompressible. The porous medium considered in the study is treated as homogeneous, isotropic and saturated with single phase liquid. The solid matrix and fluid are considered to be in thermal equilibrium, with constant thermophysical properties. The heat

transfer by conduction along the pipe wall and radiation losses are assumed to be negligible. The governing equations of flow and heat transfer pertinent to this problem can be seen in [8]. The important parameters con- **TABLE 1.** Uncertainty of the various measured and estimated parameters

Parameters								
	L (mm)	V (Volts)	I (A)	T (K)	P (Pa)	Q (%)	V_{avg} (%)	Re (%)
Uncertain y	0.02	0.01	0.01	0.2	0.02	6.5	6.2	6.7

sidered in this study are:

$$Re_D = \frac{v_{avg} D}{\nu_f} \quad (1)$$

$$k_{eff} = k_s^{1-\alpha} k_f^\alpha \quad (2)$$

3. RESULTS AND DISCUSSIONS

Experiments have been conducted for different Reynolds number by varying the flow velocity, within the regime where Dracian law is applicable, by keeping the heat input as $Q = 150$ W. A correlation for velocity as a function of pressure drop is developed.

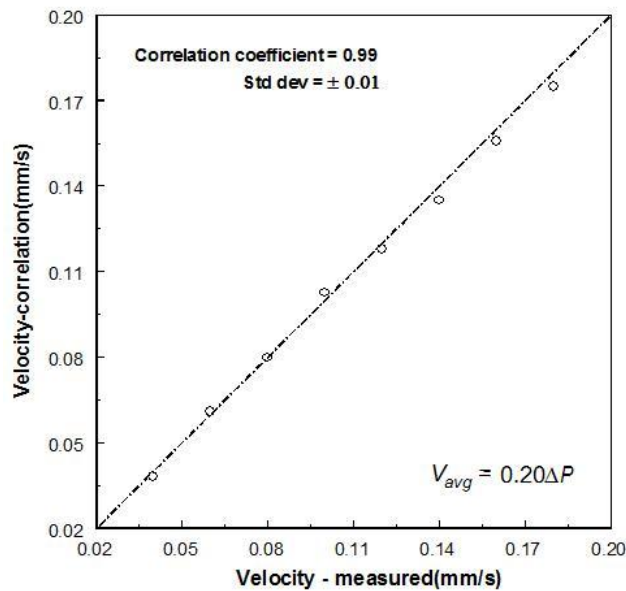


FIGURE 4. PARITY PLOT SHOWING THE EXPERIMENTALLY MEASURED AND THE CORRESPONDING VALUES ESTIMATED USING CORRELATION.

$$V_{avg} = 0.20 P$$

The correlation coefficients of the above linear fit is are 0.99 with standard error ± 0.01 . A parity plot showing the agreement of the data with the proposed correlation is illustrated in Fig. 4. A linear correlation for velocity signifies that at low Reynolds number the inertial effect can be neglected and a linear dependency is established as in accordance with Darcys law. As velocity increases the linearity vanishes and the Darcys law is to be modified by taking Forchheimer term also. Figure 5 shows the variation of temperature along the flow directions at different Reynolds number. Near to the entrance the variation is almost linear in close agreement with the variation of temperature as predicted in the case of forced convection in Hagen Poiseuille flow (without porous media) [9] subjected to constant heat flux condition. Further downstream the curve depars from this trend and becomes almost flat. This is because after a short distance porous media effect becomes dominant such that the temperature becomes uniform due to more spreading of heat resulting from the irregular flow (ie, multi-dimensional nature) pattern. The value of thermal conductivity is calculated by using the Fourier conduction equation [10], by using the measured temperature distribution in the test section of the channel. This thermal conductivity is due to the combined effect of dispersion and geometric characteristics of the porous medium. The effective thermal conductivity of the stagnant fluid alone is calculated by using eqn.2. In order find out the dispersion thermal conductivity, from the experimentally measured thermal conductivity the thermal conductivity of the stagnant fluid is subtracted to get the dispersion thermal conductivity, k_d . Figure 6 shows the variation of thermal conductivity ratio with Peclet number. As Peclet number (velocity increases) heat becomes more and more dispersed causing the thermal conductivity due to dispersion to increase. Furthermore the non linear nature of the curve is in good agreement with that has been reported by Edisath et al [11]. This further establishes the correctness of the experimental methodology employed in the present work.

4. CONCLUSIONS

Experimental investigation have been performed to study flow and heat transfer in a pipe filled with porous medium. The salient conclusions from the study are:

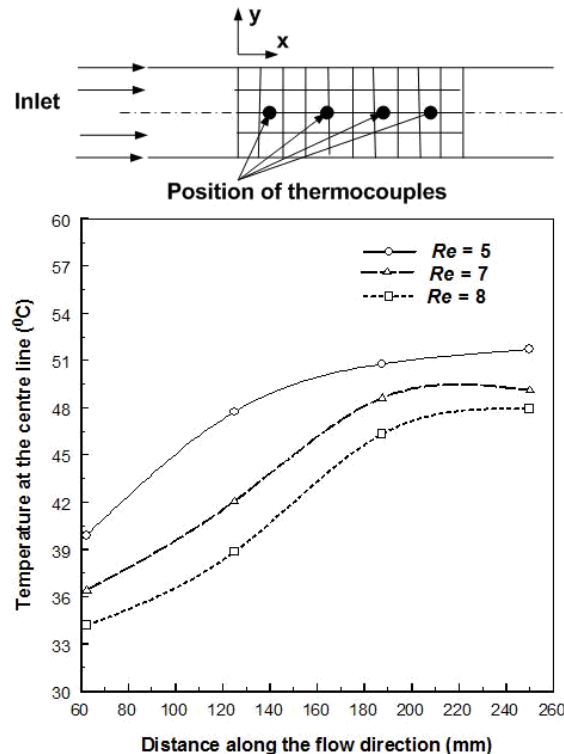


FIGURE 5. VARIATION OF FLUID TEMPERATURE AT THE MID PLANE FOR DIFFERENT REYNOLDS NUMBER

A linear correlation for velocity signifies that at low Reynolds number the inertial effect can be neglected and a linear dependency is established as in accordance with Darcys law.

At the entrance the temperature variation is almost linear, which is in close agreement with that predicted in the case of forced convection in Hagen Poiseuille flow.

Further downstream the curve departs from this trend and becomes almost flat, due to the predominance of porous media effect and the temperature becomes more or less uniform resulting in spreading of heat because of multidimensional nature of flow.

As Peclet number (velocity increases) heat becomes more dispersed causing the thermal conductivity due to dispersion to increase.

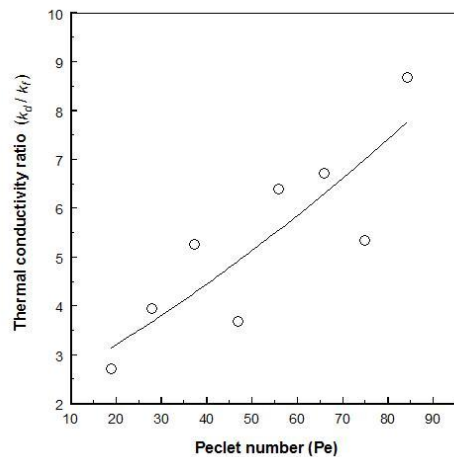


FIGURE 6. VARIATION OF THERMAL CONDUCTIVITY RATIO WITH PECELET NUMBER.

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