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An Experimental Investigation of Heat Transfer Performance for Forced Convection of Water in a Horizontal pipe partially filled with a Porous Medium

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Abstract: *In this paper, heat transfer in porous media under forced convection of water flow has been studied experimentally. A total of 36 sets of heat transfer experiments by varying the porosity, area and position have been conducted. cycle averaged local nusselt numbers and pressure drop are obtained by measuring the bulk temperature and pressure at the inlet and outlet cross sections. The porous inserts' used in this study is made of packed steel balls. The primary purpose of conducting this experiment was to find out how the Nusselt number varies with porosity, area and position. Maximum Augmentation in heat transfer with minimum pressure drop was observed for core of diameter 55mm with porosity 0.44 which was around 4.6 times higher as compared to clear flow case where no porous materials are used. On calculations, the 43.5mm diameter core insert with 0.45 porosity (6.35mm steel balls) had a ΔP/Nu value equal to 159.14 N\m^2. This was the least ΔP/Nu value of all the different combinations of area, porous insert design and porosity*
Keywords: *Heat Transfer, Porous Media, Nusselt Number*

I. Introduction

Energy saving is of primary importance in design of heat exchanger. This has severely intensified the demand for high performance heat exchangers. Significant efforts are therefore being made to improve the performance of heat exchangers. Its main purpose is the exchange of heat from one body to another, and hence it is used in both cooling and heating applications. Many researches have been carried out in order to improve the heat transfer and thermal performance of heat exchangers in order to reduce the cost and space required for its installation and working. Among several methods used, passive method of heat transfer enhancement is the main area of investigation for most of the researchers. Creating turbulence or modifying the fluid stream by using some geometry as a hindrance in the fluid path causes enhancement in heat transfer. At the same time it is also important to control the pressure drop due to these disturbances which causes a rise in friction factor and finally affects the thermal performance of heat exchangers.

Looking at the previous research gap and survey for enhancing heat transfer, it has been found that using porous medium as hindrance to the flow will enhance heat transfer when compared to flow of water without any medium as hindrance. Also, in order to reduce pressure drop, test section is to be partially filled with porous In the development of modern industrial world, tremendous works on heat enhancement or optimization have been conducted and a large number of techniques for convective heat transfer enhancement have been developed since 1970s.B.I.Pavel, and A.A. Mohamad **[2]** numerically investigated the problem of heat transfer enhancement for a laminar flow in a 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 can be increased with a reasonable pressure drop and thermally developing length can be reduced by 50% or more. This partially filling method works better than the fully filled one. A.A. Mohamad[1] further investigated the enhanced heat transfer effect of metallic porous materials that are inserted into the core of a pipe with constant and uniform heat flux experimentally and numerically. The result obtained showed that, higher heat transfer rates can be achieved using porous inserts whose diameters approach the diameters of the pipe and it is very important to get the accurate physical parameters of a porous materials from the experiment for a successful numerical simulation.**Hetsroni et al.[3]** experimentally investigated the heat transfer and pressure drop in a rectangular channel with low porosity sintered porous inserts. The results showed that the heat sink has good performance of heat transfer, when it also leads to a drastic increase in the pumping power.

Liu et al.[4] developed the new concept of enhanced heat transfer in the core flow along a tube. He believes that the core flow of tubes is worthy to be well used for heat transfer augmentation. The most way is to make temperatures 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. At the same time, it is necessary to: (a) minimize the velocity gradient of the tube flow for avoiding excessive fluid shear stress; (b) keep hydrodynamic boundary apart from the disturbance for preventing redundant loss of fluid momentum; and (c) interrupt the continuously extended surfaces frictional resistance. So, the essentials of the method can be summarized as: (a) making temperature uniform in the core flow: (b) not to increase velocity gradient in the flow field; (c) not to disrupt fluid near the boundary; (d) not to extend continuous surface on the wall. Z.F. Huang **et al**.[5] the flow resistance and heat transfer characteristics of the air flow for laminar to fully turbulent ranges of Reynolds numbers are investigated experimentally and numerically .The effect of porous radius ratio on the heat transfer performance is studied in numerical simulation. Both numerical and experimental results show that the convective heat transfer is considerably enhanced by the porous inserts of an approximate diameter with the tube and the corresponding flow resistance increases in a reasonable extent especially in laminar flow. It shows that the core flow enhancement is an efficacious method for enhancing heat transfer. **S.N. Sarada, A.V.S.R. Raju and K.K. Radha[6]** performed experimentally and numerically heat transfer analysis in a tube having air as the fluid. Porous medium made using mesh screens are placed at varying distances from each other. Also, the sizes of the meshes are varied in order to obtain varying values of heat transfer which is finally compared with the heat transfer value obtained by performing the experiment without any porous mesh screens. Nusselt number vs. Reynolds number graph and Pressure drop vs. Reynolds number graph are plotted for different R_p values. It was observed that the Nusselts number increases with an increase in R_p value and Pressure drop also increases with an increase in the R_p value.

Mehmet Turgay Pamuk and Mustafa Ozdemir [7] studied heat transfer while the flow of water is oscillated through the test pipe. Metal balls of 1mm and 3mm are used to obtain different values of porosity of the inserts. The frequencies of flow are 5 Hz, 10 Hz and 15 Hz. It was observed that the Nusselt Number increases along with an increase of Reynolds number for a particular value of oscillation. Also the Nusselt number value increased for an increase of ball diameter from 1mm to 3mm.

S Ashok Kumar and M R Rajkumar [8] conducted experiments to study flow and heat transfer characteristics in a pipe, filled with porous medium under constant heat flux condition. Packed steel balls are used to create a porous medium and water is used as the fluid under study. Effect of Reynolds number on flow and heat transfer characteristics is studied. Variation of fluid temperature at the mid plain for different Reynolds number is plotted graphically.

Based on the concept of heat transfer enhancement elaborated above, the porous media are considered to be a kind of satisfying inserts for enhancing heat transfer in the pipe flow, for its excellent performance. Lots of investigation has proven that partially filling a duct or channel with porous media is an effective method for heat transfer enhancement.

II. Problem Definition

It is seen from the literature review that the performance of completely filled porous insert techniques in the stand point of heat transfer rate especially for pipes are experimentally investigated and on the other hand experimental investigations for forced convection in a pipe partially filled with a porous medium for core is limited and with annular inserts are nearly absent. Hence, presently, the main aim of this work is to determine experimentally, the position, thickness and volumetric porosity for a porous medium insert which optimizes heat transfer for forced convection of water in a horizontal pipe maintained under constant heat flux condition.

III. Experimental Setup

Fig 1. Photographof the Experimental Setup

The experimental setup was designed and fabricated depending on the requirement and constraints of the experiment. The diameter of the setup was kept large to accommodate the core and annular porous material. To compensate for the large diameter, the flow rate was reduced to make sure that the flow through the pipe was laminar. The inlet section was made long to serve as a flow straightener and obtain fully developed flow through the pipe. The outlet section was made long to prevent errors in reading of outlet pressure due to a sudden contraction at the outlet.

Regulated water flow rate is maintained through the pipe using 0.5 HP pump The inlet pipe is made of ¾ inch PVC pipe... The inlet pipe leads to a flow straightener where small brass tubes of 8 mm diameter are placed so as to remove eddies and to provide axially uniform flow. The test section of the equipment is where the porous material is inserted. It is 300 mm long and has a diameter of 85mm.. The test section has nichrome band heaters on it to provide a constant heat flux. The band heater is covered with asbestos rope to provide insulation and reduce heat loss to the surrounding. The equipment uses K-type thermocouple (chromel-alumel). It has a range of −200 °C to +1350 °C but provides most accurate results between 50°C and 150°C. The primary reason for using the K-type thermocouple is the fact that they are resistant to oxidization, even under a humid environment and high temperatures. A total of nine thermocouples are used in various regions to measure wall temperature, water inlet, water outlet.. A knob switch is used to toggle between thermocouples and the output is displayed on a temperature indicator. Two pressure gauges are used to measure inlet and outlet water pressure. and have a least count of 0.05 kg/(cm^2).A rota meter is used to measure the water flow through the pipe. The pipe measures the flow in litres per minute and has a least count of 0.25 lpm.

A dimmer stat is used to control total power supplied to the band heater.. The presence of nichrome and nickel in the heating element prevent oxidation at high temperatures. The heater capacity is 1200W.

The flow control valve used is a gate valve. It is used to limit the water flow rate through the equipment.The insulating rope is made of asbestos. It is wound around the heater to prevent heat loss to the surrounding. The Thermal conductivity of asbestos rope is 0.04 W/ (m-K).

The primary purpose of conducting this experiment was to find out how the Nusselt number varies with porosity, area and position. To obtain the variation in Nusselt number with area, the diameter of the cores were varied. To have a comparison between the position, the areas of the core and the annulus were kept the same. The core diameters were 43.5mm, 49.6mm and 55mm. The corresponding annulus diameters were 72mm, 69mm and 65mm., these cores and annulus were filled with steel metallic balls of porosity 0.44 and 0.45.The different parameters were mixed and matched to obtain readings with all different combinations of porosity, position and area. The porous inserts' outer was made with perforated metal sheet. The sheets were rolled to the required diameter and welded for strength. This insert was placed into the test section of the experimental setup. The experimental setup has 6 thermocouples on the surface to measure wall temperature and 3 inside the test section to measure bulk temperature of the fluid.

Two pressure gauges measured the inlet and outlet pressure of the water to obtain the pressure drop.

The current and water flow is turned on once the insert is in place and the experiment is carried out when the setup reaches steady state condition. The values of the temperature, pressure and flow rate are then tabulated. The Nusselt number is then calculated and the results are analysed graphically.

3.1 Heat carried away by water

$\dot{m}C_p\Delta T_w = \frac{1}{24}$x 4179.25 x 6

=1030.5778watt

3.2 Heat transferred by convection

$hA(T_s\text{-}T_\infty)$ = h x Π x 0.085 x 0.3 x (55.2-32.6)

= 1.81 x h watt

3.3 Heat Transfer Co-efficient

Heat carried away by water = Heat transferred by convection

$\dot{m}C_p\Delta T_w = hA(T_s\text{-}T_\infty)$

1030.5778 = 1.81 x h

h = 569.38W/m^2-K

3.6.2.5 Nusselt Number and Reynolds Number

Nusselt Number,

$$Nu = \frac{hD}{k}$$

$$= \frac{569.8 \: X \: 0.085}{0.6338}$$

= 75.64

Reynolds number,

$$Re = \frac{vD}{\nu}$$

$$= \frac{0.0073 \, X \, 0.085}{5.87 \, X \, 10{-}7}$$

= 1057.10

IV. Experimental Uncertainty

A good experiment is considered to be one in which all the pertinent variables of a phenomenon except one are held constant and the phenomenon is measured as the single variable is changed. Any observed variations are then a function only of the parameter under test. The quality of the information is indicated by the quoted uncertainty in the data.The method is based on a careful specification of the uncertainties in the various primary experimental measurements. A more precise method of estimating uncertainty in experimental results has been presented by Kline and McClintock.

Suppose a set of measurements is made and the uncertainty in each measurement may be expressed with the same odds. These measurements are then used to calculate some desired result of the experiments. We wish to estimate the uncertainty in the calculated result on the basis of the uncertainties in the primary measurements. The result *R* is a given function of the independent variables *x*1, *x*2, *x*3 . . . *xn*. Thus,

I. $R = R(x_1, x_2, x_3 . . . x_n)$

Let W_R be the uncertainty in the result and w_1, w_2, w_3,………, wn be the uncertainties in the independent variables. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given as

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2}$$

Uncertainty = ΔNu / Nu

$$\text{Uncertainty} = \sqrt{\left(\frac{\Delta \dot{m}}{\dot{m}}\right)2 + \left(\frac{\Delta Cp}{Cp}\right)2 + \left(\frac{\Delta\Delta Tw}{\Delta Tw}\right)2 + \left(\frac{\Delta A}{A}\right)2 + \left(\frac{\Delta\Delta Tc}{\Delta Tc}\right)2 + \left(\frac{\Delta D}{D}\right)2 + \left(\frac{\Delta K}{K}\right)2}$$

$$= \sqrt{\left(\frac{\frac{0.25}{60}}{\frac{1}{24}}\right)2 + \left(\frac{0.01}{4178.61}\right)2 + \left(\frac{0.1}{1.2}\right)2 + \left(\frac{10-4 \times 10-4}{0.0801}\right)2 + \left(\frac{0.1}{21}\right)2 + \left(\frac{10-4}{85x\ 10-3}\right)2 + \left(\frac{0.0001}{0.6348}\right)2}$$

$$= \sqrt{0.017}$$

= ± 0.13

Uncertainty = ± 0.13 or ± 13%

ΔNu/ Nu = 0.13

ΔNu = 0.13× 16.43

ΔNu = ± 2.14

Therefore the actual Nusselt number would range between

Nu = 16.43 ± 2.14

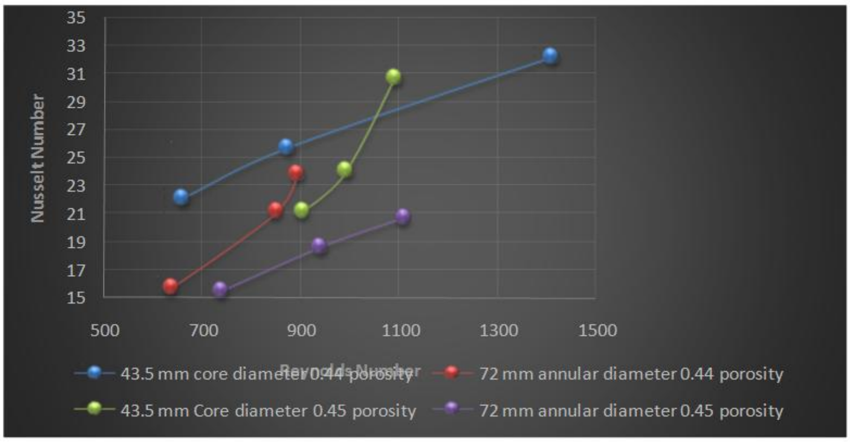
Where ±2.14 is the uncertainty in the actual value of the Nusselt number.

The percentage uncertainty is ±13%

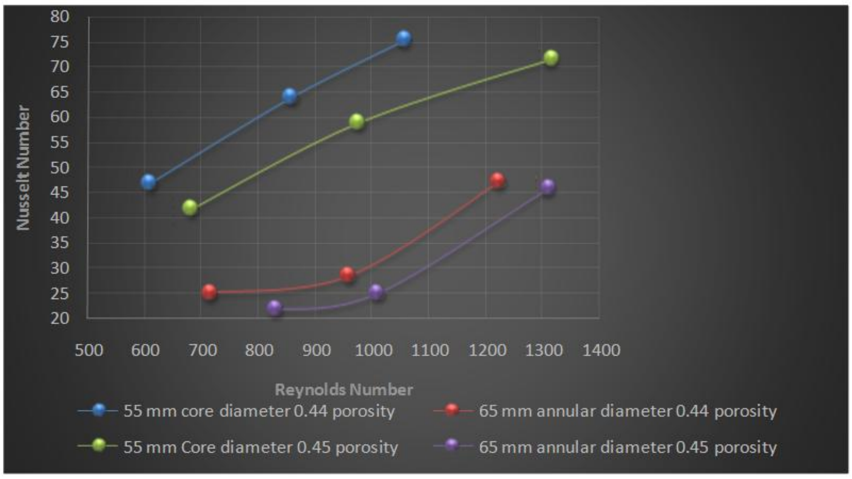
V. Experimental Set Results And Discussion

On the basis of experimental investigation different results have been obtained for different set of inserts. Variation of heat transfer and pressure drop on the basis of different flow parameters is through experimental data. These data are further used to plot graphs which show variation of heat transfer and pressure drop with respect to different flow parameters. There in a noticed increase in heat transfer with the use of porous inserts when compared to no porous insert condition. The reason for these are increased turbulence, increased velocity of fluid due to decrease in effective area, mixing of the fluid due to obstructions,

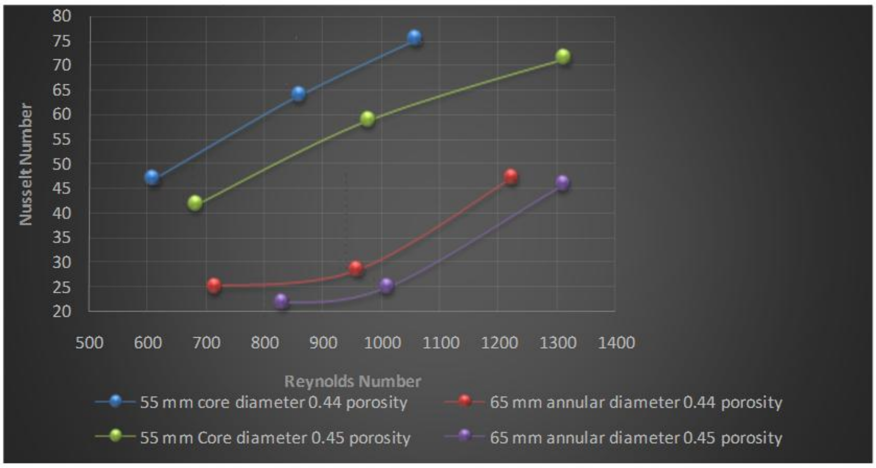
5.1 Nusselt Number vs Reynolds Number (constant area, varying porosity)



Graph 5.1 Plot of Nusselt number vs Reynold number for different porosity with same area of 0.00149 m^2



Graph 5.2 Plot of Nusselt Number vs Reynolds Number for different porosity with same area of 0.00193 m^2

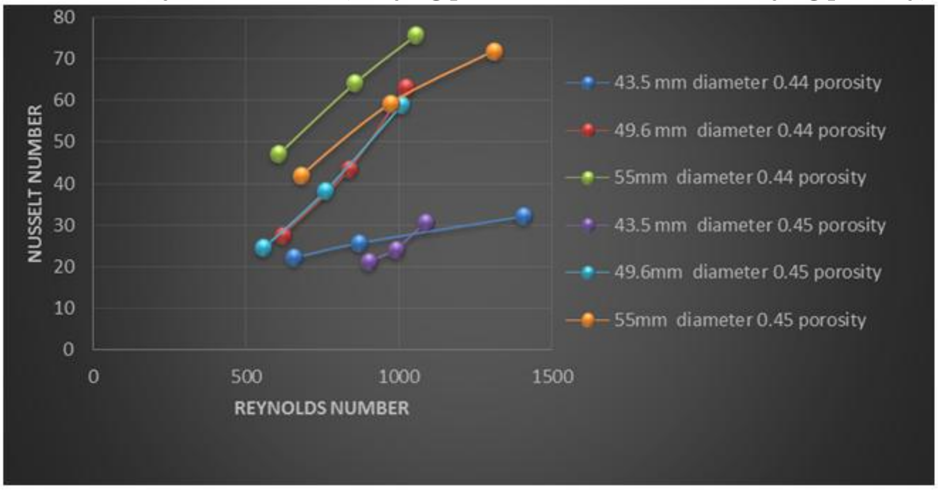


Graph 5.3 Plot of Nusselt number Vs Reynolds number for different porosity with same area of 0.00237 m^2

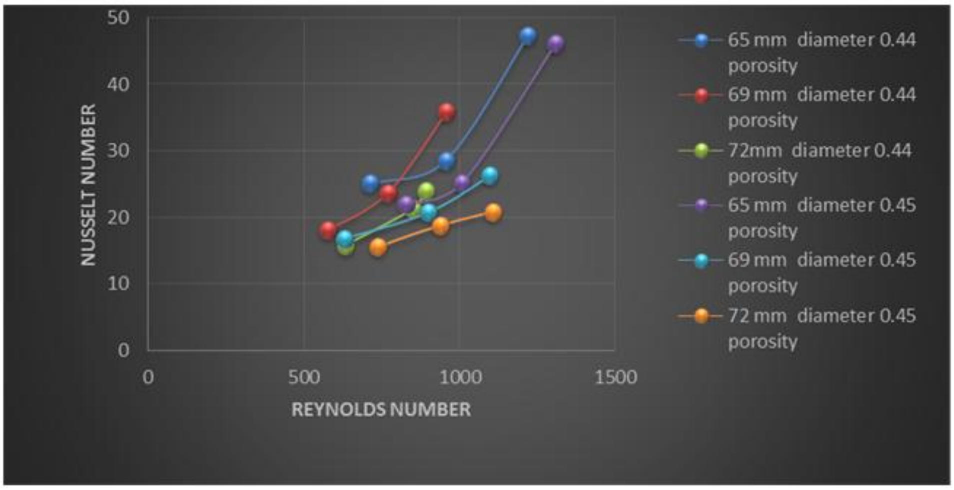
Above three graphs shows that Nusselt number increases with an increase in Reynolds Number. This is mostly attributed to the fact that the increase in mass flow rate results in more heat being carried away by the water flowing through the pipe.

Nusselt number increases with an increase in the effective area of the porous media. The position also governs the Nusselt Number variation. For constant area, the core offers better heat transfer when compared to the annular section.For a subsequent increase in area, there is on an average a 42.6% increase in heat transfer.

5.3 Nusselt Number vs Reynolds number (Varying porous medium size and varying porosity)



Graph 5.4 plot of Nusselt number vs Reynolds number for different core diameter with varying porosity



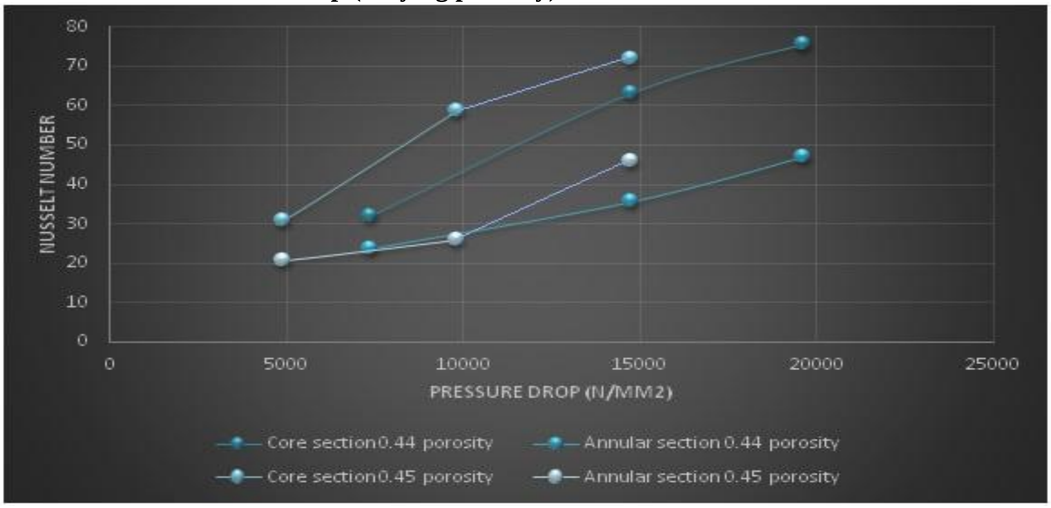
Graph 5.5 Plot of Nusselt number vs Reynolds number for different annular diameter with varying porosity

The above graphs shows the plot of Nusselts number vs Reynolds number for all the cores/annular sections and the two porosity values. It is evident that for a particular area of the porous medium, the 0.44 porosity give better heat transfer when compared to the 0.45 porosity. The reason being the lesser area between two balls for the smaller sized 4.76mm balls. As the area decreases, the velocity increases to keep the discharge of water a constant. The increased velocity coupled with the Eddy current produced due to obstruction of water from flowing in a straight path 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. The Nusselt number decreases by 7.8% and 13.5% respectively for the core and annular design with a change in porosity from 0.44 to 0.45 keeping area as constant.The analysis also reveals that an increased area of porous medium results in increased heat transfer. This happens because the presence of the porous in the centre reduces the effective area for the water to flow through. Lower area with a constant discharge quantity results in larger flow velocity. As the velocity increases, there is an increase in turbulence generated. And subsequently, larger heat transfer due to the presence of a porous material.

As area of the core/annulus increases there is on an average a 42.6% increase in heat transfer.

Analysis between the same area core and annular section with the same sized balls also reveals that the presence of the porous medium in the form of a core gives a better heat transfer and better Nusselt number. The reason for this is that the presence of the core in the centre region pushes most of the water to flow close to the wall to which a constant heat flux is supplied. This facilitates better absorption of heat from the wall surface through convective heat transfer. It is also noticed that the core gives about 67% more heat transfer when compared to the annular section inserted inside the test section.

5.4 Nusselt Number vs Pressure drop (varying porosity)



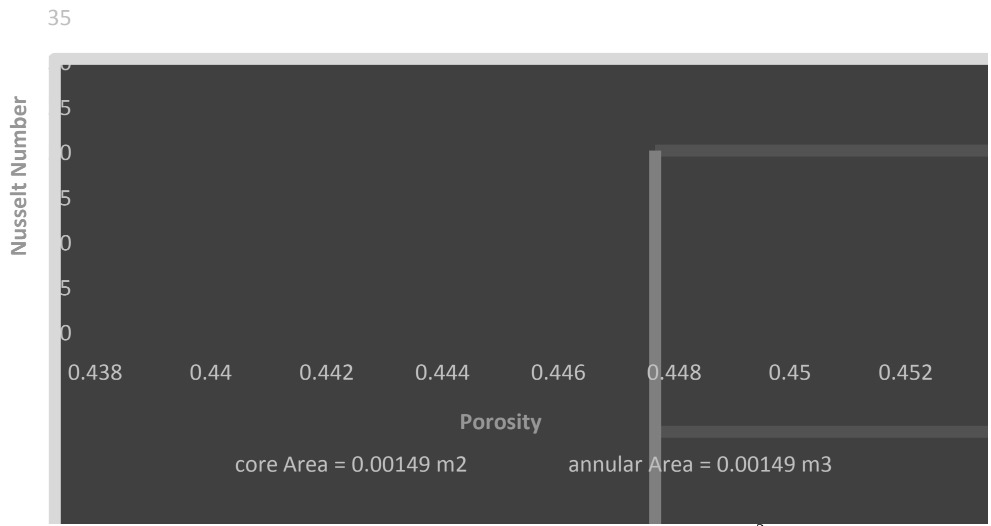
Graph 5.6 Nusselt number Vs Pressure drop for varying porosity

The above graph on shows the variation of Nusselt number vs pressure drop in the test section due to the presence of the porous medium. There is a clear indication that the core section offers more pressure drop in comparison with the annular section. The reason for this is attributed to more flow in the centre region of the pipe. The core provides a large pressure drop being right in the path of the bulk amount of water flow.

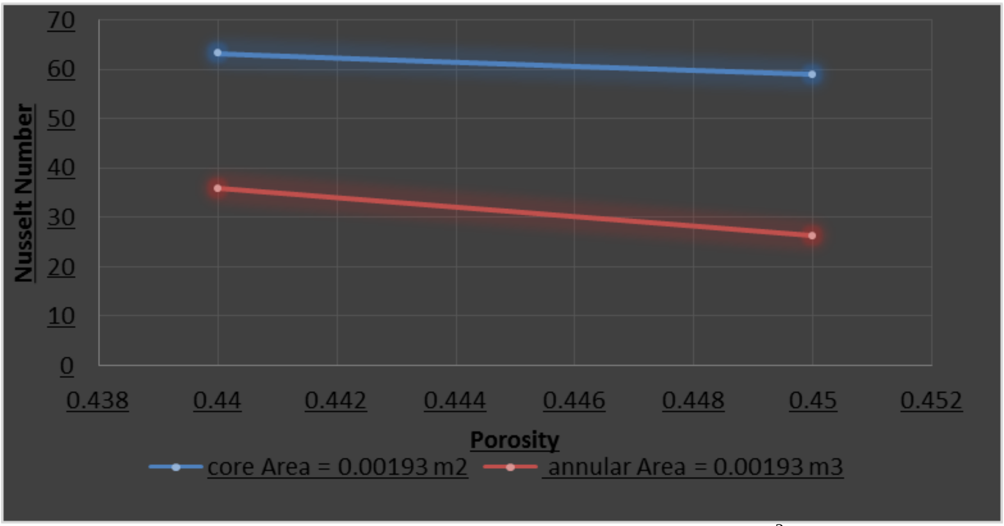
On an average, the core offers 1.4 times more pressure drop when compared to the annular section, keeping the ball size constant.Also, a larger area of the porous medium causes a larger pressure drop.

The porosity also plays a role in the value of the pressure drop. The smaller sized 4.76 mm balls having porosity 0.44 are packed more closely when compared to the 6.35mm balls having porosity 0.45. This causes a larger pressure drop in the 4.76mm balls. The closer packed structure requires the water to use more force to pass through the smaller gapsbetween the 4.76mm steel balls. Hence there is a larger pressure drop in the 4.76mm balls.The pressure drop per unit Nusselt number is minimum for the 55mm diameter core porous section with a porosity of 0.44.

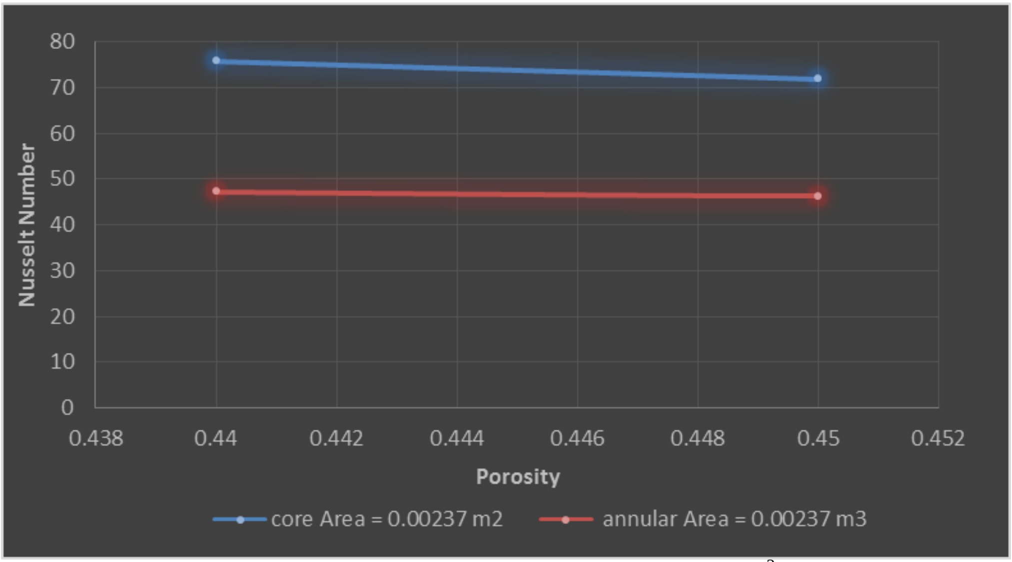
5.5 Nusselt Number vs Porosity (varying areas)



Graph 5.9 Nusselt Number vs Porosity (area=0.00149m^2)



Graph 5.10 Nusselt Number vs Porosity (area=0.00193m^2)

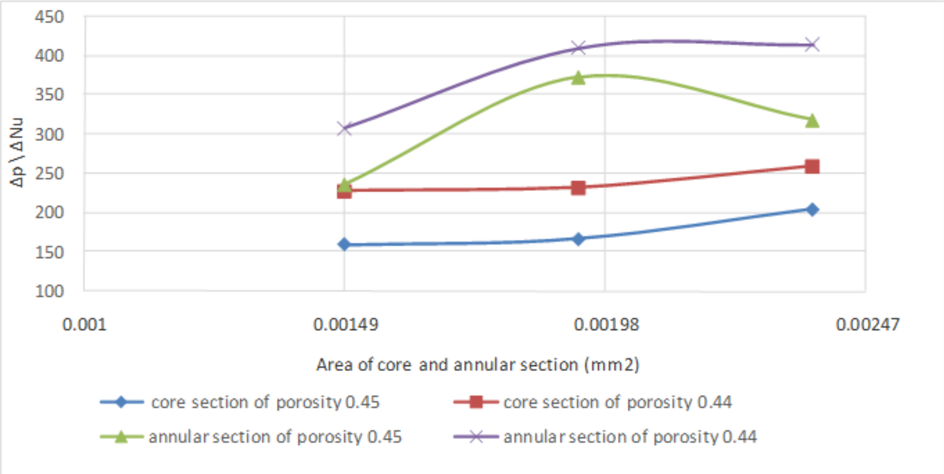


Graph 5.11 Nusselt Number vs Porosity (area=0.00237m^2)

The Nusselt number increases with a decrease in porosity of the core for a constant area of the core. This is due to the reduction in gap between adjacent balls which increases the Eddy development and turbulences. There is on an average of 7.8% reduction in Nusselt number when the porosity increases from 0.44 to 0.45 for core.The same pattern is noticed in the annular section. However the Nusselt number decreases by 13.5% for an increase in porosity from 0.44 and 0.45.

The previous three graphs are a plot of the Nusselt Number vs pressure drop with varying porosity and different core design.These graphs clearly depict that the core shaped porous insert has more heat transfer for a particular area when compared to the annular section even with the variation in porosity.There is an average of 42.6% increase in heat transfer when there is an increase in area from 0.00149m^2 to 0.00193m^2 or from 0.00193m^2 to 0.00237m^2.

5.7 Optimization



Graph 5.12 Optimization

To optimize and find the best combination of porous insert size, design and porosity, we divided the pressure drop by the Nusselt number. The insert with the least pressure drop per unit Nusselt number would give us the best porous insert.

On calculations, the 43.5mm diameter core insert with 0.45 porosity (6.35mm steel balls) had a ΔP/Nu value equal to 159.14 N\m^2. This was the least ΔP/Nu value of all the different combinations of area, porous insert design and porosity.

VI. Conclusion

The performing of the experiment has led us to reach the following conclusions:

- There is a definite increase in heat transfer with the use of porous inserts in the experimental setup. The insert of core section having diameter 55mm with porosity 0.44 which found to be around 4.6 times higher as compared to clear flow case where no porous materials are used

There is an increase in Nusselts 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 42.6%
- There is a variation in Nusselt number with design as well. The core shaped porous insert offers better heat transfer when compared to the annulus shaped porous insert. This is again accompanied with a greater pressure drop.
  The increase in heat transfer for same effective area and for same porosity is on an average 67% greater for the core shaped insert when compared to the annulus shaped insert. Consequently, the pressure drop using the core is 1.4 times the pressure drop using the annulus
- The Nusselt number also increases with a decrease in porosity of the metal balls. The 4.76mm steel balls having porosity 0.44 offers better heat transfer when compared to the 6.35mm steel balls having porosity 0.45. The 0.44 porosity inserts offer 10.7% more heat transfer when compared to the 0.45 porosity inserts
- To optimize and find the best combination of porous insert size, design and porosity, we divided the pressure drop by the Nusselt number. The insert with the least pressure drop per unit Nusselt number would give us the best porous insert.
  On calculations, the 43.5mm diameter core insert with 0.45 porosity (6.35mm steel balls) had a ΔP/Nu value equal to 159.14 N\m^2. This was the least ΔP/Nu value of all the different combinations of area, porous insert design and porosity

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