IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Impact Of Porosities Of Porous Inserts For Varying Reynold's Number On Pressure Drop And Heat Transfer Rates In Pipes: A Numerical Analysis

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Abstract

This study investigates the impact of porous inserts in forced convection systems on heat transfer enhancements. ANSYS Fluent 2021 is used to study the effects of varying porous layer thickness and Reynolds number on pressure drop and heat transfer rates in pipes. Porous media of varying radius ratios of R = 0.8, 0.6, 0.4, and 0.2 were analyzed under constant temperature conditions. The results from the study found that increasing the thickness of the porous medium generally enhances the peak axial velocity, shifts it closer to the pipe wall, and improves overall heat conduction efficiency. A significant temperature gradient near the pipe wall was observed, indicating an increase in the Nusselt number and overall heat transfer efficiency. Also, there exists an optimal porous thickness beyond which no significant increase in the Nusselt number occurs. The study found that the influence of porosity on heat transfer is less pronounced compared to that of porous layer thickness. The Performance Evaluation Criteria (PEC) indicates that porous media inserts substantially enhance the overall heat transfer.

Index Terms - Porous Media, Porous Layer Thickness, Thermal Dispersion, Performance Evaluation Criteria

INTRODUCTION

The use of porous inserts in forced convection systems has emerged as an effective approach for enhancing heat transfer. Efficient heat transfer mechanisms are crucial in many engineering applications. Porous materials are particularly valuable due to their ability to modify flow distribution and thermal conductivity, leading to improved thermal performance. This is especially important in industries ranging from electronic cooling and drying processes to more complex systems like solid matrix heat exchangers, heat pipes, and nuclear reactors. In these settings, efficient heat management is critical for both performance and safety. For instance, in nuclear reactors, porous media play a crucial role where heavy water (D2O) is used as a coolant. It passes through uranium fuel rods, which act as a porous medium, thereby improving the reactor's cooling efficiency. The porous nature of these materials allows for a more uniform temperature distribution, minimizing hot spots and preventing overheating. This is achieved through various mechanisms: redistributing flow to enhance convective heat transfer by altering the flow pathways, optimizing thermal conductivity to improve the material's heat conduction capability, and enhancing radiative heat transfer, which is particularly beneficial in high-temperature environments. The use of porous media is not confined to nuclear reactors. In heat exchangers, the inclusion of porous materials can significantly increase the heat transfer coefficient, which is vital for efficient thermal management. These materials enhance heat transfer rates by increasing the surface area available for heat exchange and reducing the boundary layer thickness. Understanding how to tailor the porosity and permeability of these inserts for heat transfer allows for customized thermal management solutions in various engineering contexts. This study investigates the application of porous media inserts in pipes to improve heat transfer. It aims to deepen the understanding of the mechanisms through which porous materials enhance thermal performance. Key factors such as porous layer thickness and porosity significantly influence heat transfer efficiency. The study seeks to optimize the design and use of these materials in thermal systems, providing valuable insights for industries that require efficient heat management solutions.

LITERATURE REVIEW

Heat exchangers are integral components in modern chemical processes, significantly influencing the overall assets involved [1]. Since heat exchangers constitute approximately half of the equipment in these processes, optimizing their efficiency is critical for energy conservation. One key approach to improving heat exchanger performance is enhancing the heat transfer coefficient between the fluid and the pipe wall. This can be done by increasing the flow velocity near the wall or by reducing the boundary layer thickness, thereby creating a larger temperature gradient. However, in the case of fully developed pipe flow, simply increasing fluid velocity has a limited effect on the radial temperature gradient near the pipe wall. Consequently, innovative heat transfer enhancement technologies have been developed [2]. Porous substrates, known for their high thermal conductivity, are widely used to enhance heat transfer in various engineering applications. The study of convective heat transfer in porous media has gained considerable attention, with numerous theoretical and experimental studies documented in the literature [3].

Mahjoob and Vafai [4] conducted an extensive analytical investigation on forced convection through a generic channel subjected to a constant heat flux, providing exact solutions for fluid and solid phases, wall surface temperature distributions, and Nusselt number correlations. Similarly, Chikh et al. [5] presented analytical solutions for fully developed flow in annular configurations partially filled with porous media. Hetsroni et al. [6] experimentally studied heat transfer and pressure drop in rectangular channels with different porosities, while Angirasa [7] demonstrated the effectiveness of porous media in enhancing heat transfer through experimental studies.
Numerical simulations have also been widely employed to study convective heat transfer in porous media. Alkam [8] conducted numerical investigations of forced convection flow in annuli partially filled with porous media, revealing an increase in the Nusselt number under these conditions. He examined steady and laminar flow in conduits fully or partially filled with porous layers under various temperature boundary conditions, concluding that heat transfer enhancement is achievable with partially filled porous media. Bhargavi et al. [9] examined how porous media affected heat transfer in fully developed flow through channels that were only partially filled with porous material. The results showed that, above a certain point, increasing the porous thickness increased the Nusselt number on the fluid side more than it decreased on the porous side. Satyamurty [10] determined the ideal porous thickness for maximizing the Nusselt number by studying forced convection in thermally developing areas of channels partially filled with porous medium.

In a numerical analysis, Mohamad [12] explored steady and laminar flow within a conduit either fully or partially filled with a porous layer under different temperature boundary conditions, noting that heat transfer enhancement could be achieved with a partially filled porous medium. The study also found that the inertia term was insignificant for Darcy numbers (Da) less than 10-4, given the specified range of other parameters. L. Rong et al. [13], in their study, investigated the impact of porous media on enhancement of heat transfer in a pipe using numerical simulations. They discovered that increasing the thickness of the porous media significantly improves heat transfer performance and fluid temperature uniformity but also increases flow resistance. The study concluded that optimizing porous media thickness can enhance heat transfer efficiency while balancing the trade-off with increased flow resistance. Chen Jinyi and Liu Botan {14}studied the relationships between the thermal dispersion and the interfacial heat transfer coefficient for turbulent convective flow in porous medium, in their research, examined the effective characteristics that are crucial to the up-scaled mathematical models of porous media, such as the longitudinal and transverse thermal dispersion and the interfacial heat transfer coefficient. Nonetheless, the majority of current correlations are derived under the assumption that fluid flow in porous media is laminar. Consequently, the study used numerical simulations to look at the longitudinal thermal dispersion and interfacial heat transfer coefficient for turbulent convective flow in porous media.

THEORY

Several basic governing equations are involved in the study of convective heat transfer in pipe flow, particularly when porous medium is added. The concepts of continuity, momentum, and heat transfer processes are explained by these equations. These formulas are essential for comprehending the dynamics of heat transport in systems with porous materials, and they are described in this section.

1.1 Continuity Equation

The continuity equation ensures the conservation of mass within the flow and can be expressed as:

$$\frac{\partial(\rho \mathrm{Ux})}{\partial x} + \frac{1}{r}\frac{\partial(\rho \mathrm{Ur})}{\partial r} = 0 \qquad (1)$$

where, ρ is the fluid density in kg/m3, u_x is the axial velocity component in m/s, u_r is the radial velocity component in m/s, and x, r and t are the axial coordinate in m, radial coordinates in m and time in s, respectively.

1.2 Momentum Equations

Equation (2) and (3) are the momentum equations in axial and radial direction respectively.

$$\frac{\partial(\rho \mathrm{Ux})}{\partial t} + \frac{1}{\varepsilon}\frac{\partial(\rho \mathrm{Ux\,Ux})}{\partial x} + + \frac{1}{r\varepsilon}\frac{\partial(r\rho \mathrm{Ux\,Ur})}{\partial x} = - \frac{\partial(\varepsilon p)}{\partial t} \qquad (2)$$

$$\frac{\partial(\rho \mathrm{Ur})}{\partial t} + \frac{1}{\varepsilon}\frac{\partial(\rho\ \mathrm{Ux\,Ur})}{\partial x} + + \frac{1}{r\varepsilon}\frac{\partial(r\ \rho\ \mathrm{Ur\,Ur})}{\partial r} = - \frac{\partial(\varepsilon\, p)}{\partial r} + \mu_{eff}\left(\frac{\partial 2\mathrm{Ur}}{\partial x2}\right) \qquad (3)$$

Where, p is the pressure in N/m2, μ_{eff} is the effective viscosity in Ns/m2, F_x and F_r are the body forces in the axial and radial directions, in N, respectively, and ϵ is the porosity of the medium.

1.3 Energy Equation

The heat transfer equation is given by,

$$\frac{\partial T}{\partial t} + \mathrm{Ux}\frac{\partial T}{\partial x} + \mathrm{Ur}\frac{\partial T}{\partial r} = \alpha\left(\frac{\partial 2\mathrm{T}}{\partial x2} + \frac{1}{r}\frac{d}{dr}\left(\mathrm{r}\frac{dT}{dr}\right)\right) \qquad (4)$$

where, T is the temperature in K, α is the thermal diffusivity in m^2/s.

1.4 Body Forces in Porous Media

The total body force F due to the presence of porous media and other external forces is given by:

$$F_w = -\frac{\mu}{K}u_w - \frac{\epsilon F_e}{\sqrt{K}}|u|u_w + \epsilon G \qquad (5)$$

Where, μ is the dynamic viscosity Ns/m2, K is the permeability of the porous medium in m2, F_e is the geometric function, G is the external body force in N, and w denotes the direction x or r.

1.5 Nusselt Number

The strength of heat transfer is evaluated based on the Nusselt number for the pipe wall. The equation for Nusselt is given by A.A Mohamad [11]

$$NU = \frac{2\left(\frac{d\theta}{dR}\right)}{Tw} = Tw - Tm \quad (6)$$

Where, U is the fluid velocity at a specific radial position, r, T is the fluid temperature at a specific radial position and R is the radius of the pipe.

Performance Evaluation Criterion (PEC)

The Performance Evaluation Criteria (PEC) is used as a comprehensive metric to study the effectiveness of enhancements in heat transfer by considering both heat transfer and flow resistance.

NUMERICAL METHOD

The study presented here investigates thermal flow in a pipe partially filled with a porous medium, simulated using ANSYS Fluent 2021. The computational domain for both the porous medium and the pipe is illustrated in Figure 1. The porous medium is considered homogeneous, isotropic, and saturated with a single-phase fluid in local equilibrium with the solid. Various configurations were studied, with the porous medium having radii of 0.8R, 0.6R, 0.4R, and 0.2R, where R represents the inner radius of the pipe. The pipe's length is set to 15 times the inner radius to ensure fully developed flow conditions at the exit. The porous insert region spans 200 mm in length, with the pipe walls in this area subjected to a constant temperature boundary condition of Tw = 400K.

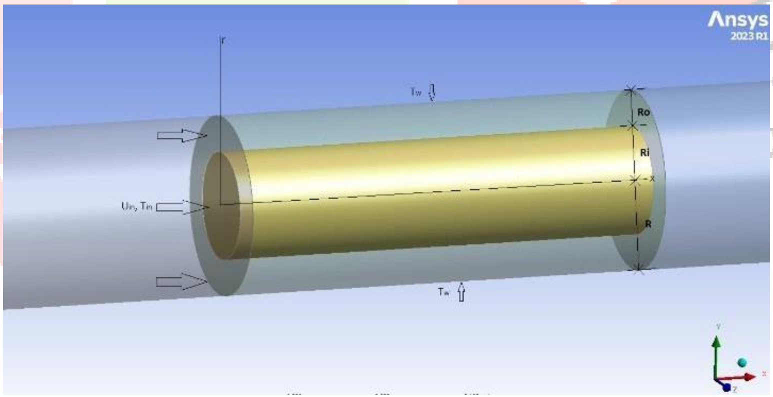


Fig. 1. Computational domain with schematics

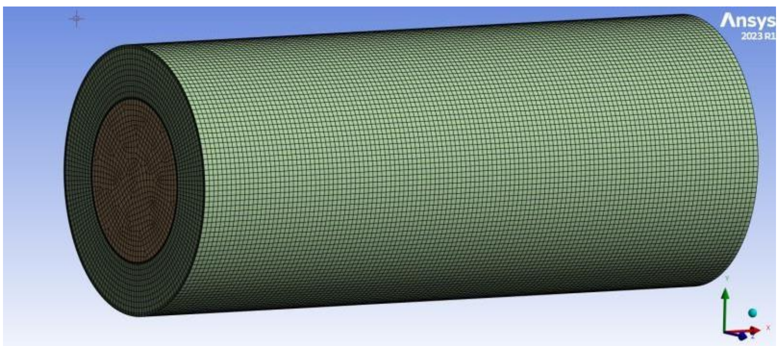


Fig. 2. Mesh on porous insert domain

A high-resolution mesh consisting of 3,019,000 elements and an inflation layer of 5 was utilized to capture detailed flow and heat transfer phenomena. This fine mesh ensures the resolution of intricate flow structures and precise calculation of temperature gradients. The high-resolution meshing improves numerical stability and reduces errors, ensuring reliable simulation outcomes. Figure 2 depicts the mesh of the region with the porous insert.

4.1 Validation

The numerical study has been validated against the work of F. Rong et al. [11]. Specifically, the flow conditions with a porous medium radius ratio (Ri) of 0.6, porosity (ϵ) of 0.6, Prandtl number (Pr) of 0.7, and Reynolds number (Re) of 100 were simulated, showing a deviation within 5% of the analytical results presented in [13]. Figure 3 compares the results for velocity ux versus radius (R) under these conditions.

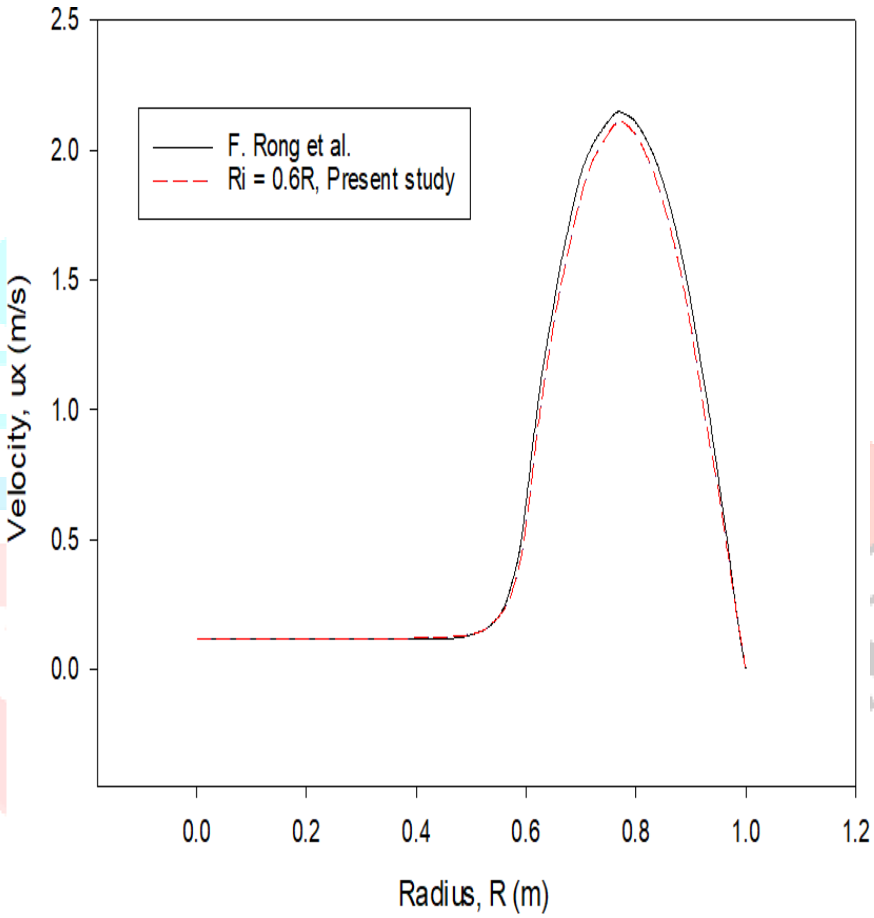
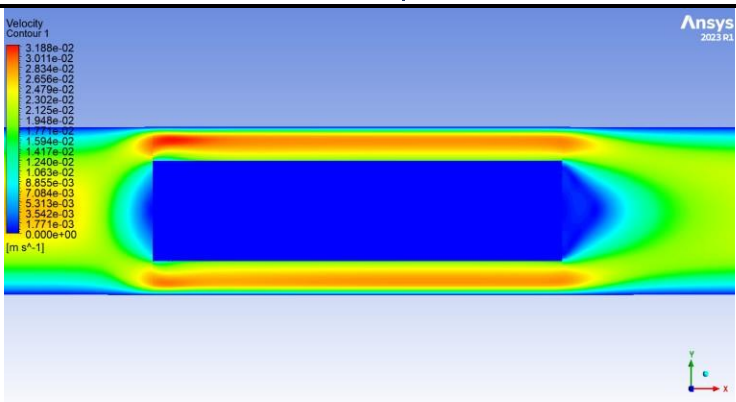


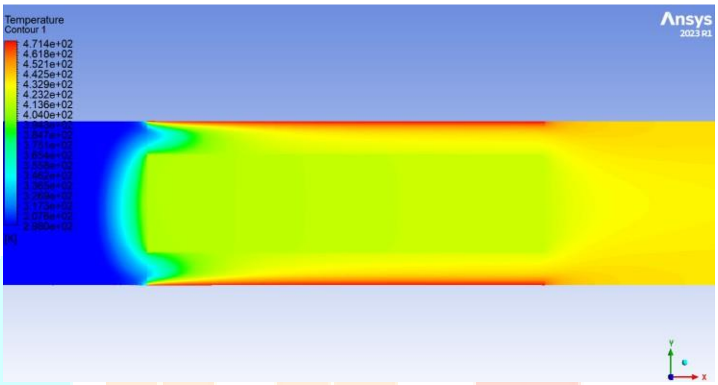
Fig. 3. Validation study

RESULTS

The study's findings for the flow conditions of Ri = 0.6, $\epsilon = 0.6$, Pr = 0.7, and Re = 100 are presented below. The velocity and temperature contours in the XY plane through the pipe's centerline are depicted in Figure 4 (a) and (b), respectively. The velocity contours indicate an increase in velocity in the annular region between the pipe wall and the porous insert, attributable to the reduced area. This phenomenon reflects the enhanced flow dynamics induced by the porous media. The temperature contours illustrate the significant influence of the porous layer on heat transfer, showing that the porous region effectively enhances thermal conductivity and facilitates heat transfer. These visualizations emphasize the importance of optimizing the characteristics of porous media to improve overall system performance.



(a)



(b)

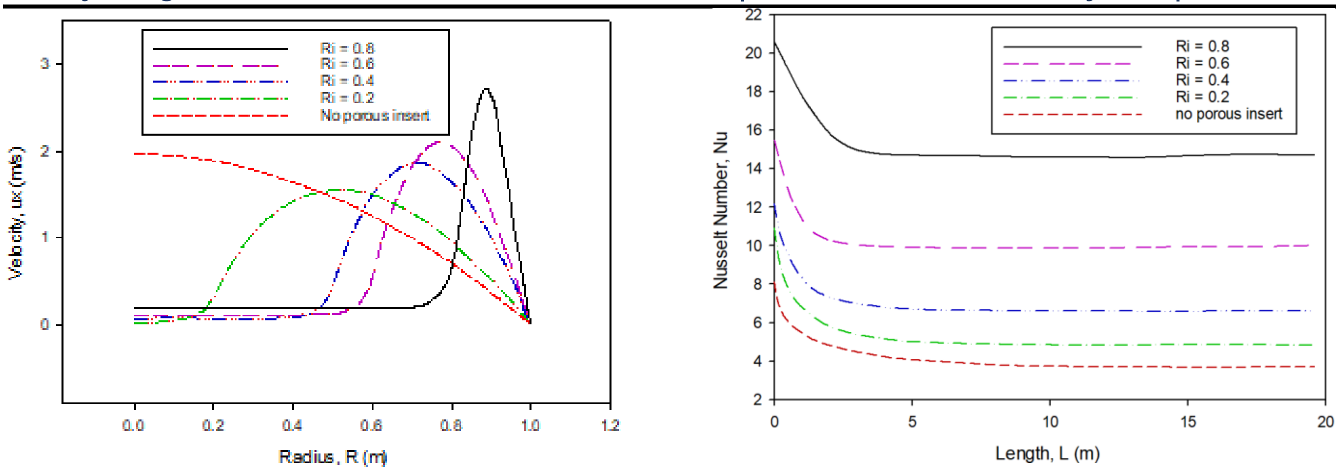
Fig. 4. Velocity and Temperature contour in the diametrical XY plane

4.2 Effect of the Porous Layer Thickness

Figure 6 presents the study's results for the flow conditions and Nusselt number distribution for porous medium radius ratios (Ri) of 0.8, 0.6, 0.4, 0.2, and 0.0 (no porous insert); with a porosity (ϵ) of 0.6; Prandtl number (Pr) of 0.7, and Reynolds number (Re) of 100. As the thickness of the porous media increases, the peak axial velocity also increases and shifts closer to the pipe wall. However, the peak velocity does not always continue to rise; it becomes constant when the pipe is entirely filled with porous media or when the thickness of the porous medium approaches the pipe's diameter. The overall conduction efficiency improves, and the temperature distribution becomes more uniform with the addition of porous media.

A significant temperature gradient appears near the pipe wall, significantly enhancing the heat transfer effect. Both the velocity and temperature gradients are larger with the porous medium than without it. The Nusselt number (Nu) increases with the thickness of the porous media, indicating enhanced convective heat transfer. The maximum heat transfer intensity with porous media can be nearly three times that of a pipe without a porous insert. Inserting porous media into the pipe center increases fluid velocity and improves heat exchange between the fluid and the pipe wall. Without porous media, most of the heat concentrates in the pipe center, leading to poor heat transfer on the pipe wall. With porous media, the heat distribution becomes more uniform. The results indicated that as the thickness of the porous media increased, the Nusselt number also increased, reflecting improved heat transfer efficiency. However, there was an optimal thickness beyond which the Nusselt number did not increase significantly, suggesting a limit to the beneficial effects of increasing the porous media thickness.

The results show that the Nusselt number ratio (Nu/Nu_0) with respect to the radius indicates that the introduction of a porous medium significantly enhances heat transfer efficiency, as evidenced by an increase in the Nu/Nu_0 ratio in Figure 6. This enhancement is attributed to the porous structure's ability to disrupt the thermal boundary layer, which improves convective heat transfer.

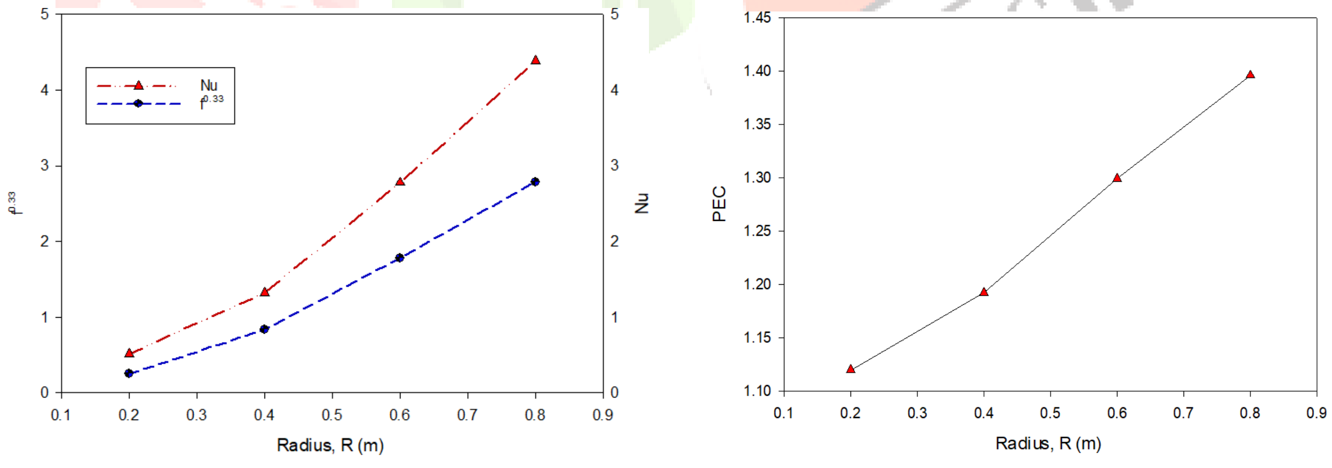


(a) (b)

Fig. 5. (a) Velocity vs. Radius for different Radius, Ri and (b) Nusselt number distribution along porous media length

The drag coefficient, representing the resistance to fluid flow, also varied with the thickness of the porous media. The study observed that the drag coefficient increased as the porous layer thickness increased. The drag coefficient ratio (f/f_0) assesses the increase in flow resistance due to the porous medium compared to a blank pipe. It is found that flow resistance, indicated by the drag coefficient, increases with the thickness of the porous medium. This increase in resistance is linked to the larger contact area between the fluid and the porous medium, which causes more frictional losses and requires more pumping power. Therefore, even if heat transfer is enhanced, the increased drag must be carefully managed to maintain system efficiency.

The results showed that the PEC value increased with the porous layer thickness up to a certain point, indicating that the heat transfer benefits outweighed the added flow resistance. However, beyond an optimal thickness, the PEC value began to decrease, suggesting that the additional drag introduced by the thicker porous media reduced the overall efficiency of the system.



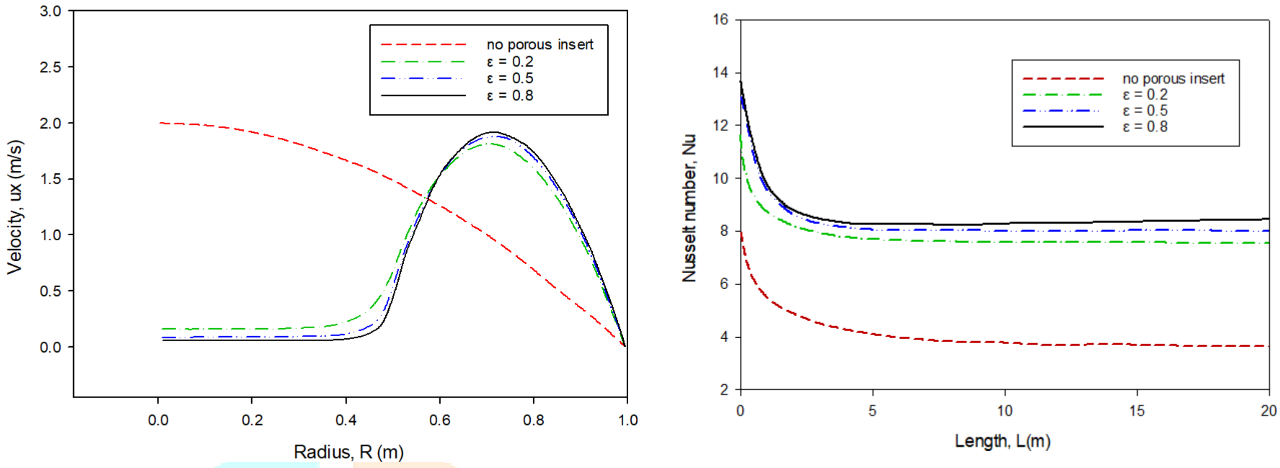
(a) (b)

Fig. 6. (a) Nu/Nu0 and $(f/f0)^3$ for R = 0.2, 0.4, 0.6, and 0.8 (b) PEC for R = 0.2, 0.4, 0.6, and 0.8.

4.3 Effect of Porosity

The variation on dimensionless velocity, temperature and Nusselt number in the fully developed region are given in Fig. 7. The study is done for porosity, ε = 0.2, 0.4, 0.6 and 0.8 for Ri =0.5, Pr = 0.7 and Re =100. As shown in Fig.

7, as the porosity is increasing the efficiency of heat transfer also increases. But it is also found that the influence of porosity is very less compared to the effect for different porous layer thickness. The results are consistent with the study by L. Rong et al. [13].

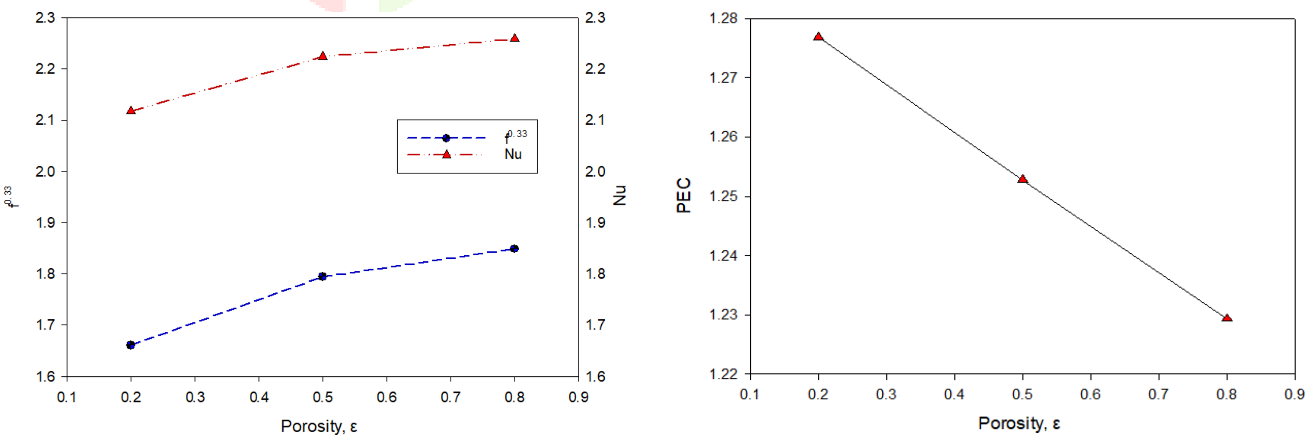


(a) (b)

Fig. 7. (a) Velocity vs. Radius for different Radius, Ri and (b) Nusselt number distribution along porous media length

It is observed that the variation in the Performance Evaluation Criteria (PEC) value with different porosity levels was minimal, suggesting that the change in porosity had a limited impact on the overall performance of the system in terms of the balance between heat transfer and flow resistance. This consistency was reflected in the velocity and temperature fields, where variations due to changes in porosity were also minor. It is shown in the Fig. 8.

The PEC values for all the given porosity levels were greater than 1, suggesting that the porous media insert significantly improved the comprehensive performance compared to a pipe without porous insert. This enhancement demonstrates that the porous media effectively increased heat transfer efficiency, outweighing the negative effects of increased flow resistance, thereby providing a net positive impact on system performance.



(a) (b)

Fig. 8. (a) Nu/Nu0 and $(f/f0)^3$ for R = 0.2, 0.4, 0.6, and 0.8 (b) PEC for R = 0.2, 0.4, 0.6, and 0.8

CONCLUSION

The study explored the impact of porous media on heat transfer enhancement in a pipe using numerical simulations. The study focused on the effects of varying porous layer thickness, characterized by the ratio of porous layer thickness to pipe radius under the conditions (ϵ=0.6, Re =100, and Pr = 0.7. The findings reveal that increasing the thickness of the porous media significantly enhances heat transfer performance and fluid temperature uniformity.

This improvement is attributed to the increased axial fluid velocity and more uniform temperature distribution facilitated by the porous insert. However, there is a limit to this enhancement, as the axial velocity peak value does not always continue to increase with increasing porous media thickness. The Nusselt number (Nu), which serves as an indicator of convective heat transfer strength, increases with porous media thickness, reaching up to three times the intensity of a pipe without porous insert. However, there is an optimal thickness beyond which the benefits plateau, indicating a limit to the effectiveness of increasing the porous media thickness.

The drag coefficient, representing flow resistance, also increased with porous media thickness. This increase is linked to a larger contact area between the fluid and the porous medium, resulting in higher frictional losses and a need for more pumping power. The Performance Evaluation Criteria (PEC) value initially increased with the thickness of the porous layer, suggesting that the heat transfer benefits outweighed the added flow resistance. However, beyond an optimal thickness, the PEC value declined, indicating that the increased drag began to offset the heat transfer gains. In case of porosity, it is found that while increasing porosity enhanced heat transfer efficiency, its influence was less significant compared to the effects of varying porous layer thickness. The PEC values remained consistently above 1 across different porosity levels, underscoring the net positive impact of porous media on system performance, despite the increased flow resistance.

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