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Numerical Analysis Of How The Thickness Of The Porous Layer Affects Heat Transmission In Pipes

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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 porous layer thickness and Reynolds number on pressure drop and heat transfer rate when air is passed through pipe fitted with porous inserts and subjected to constant heat temperature are studied and compared with the clear flow case without porous material.

Index Terms - Porous Media, Porous Layer Thickness, Thermal Dispersion

Introduction

The use of porous inserts in forced convection systems is an effective technique for enhancing heat transfer, making it applicable to a wide range of engineering fields. The employment of different types of porous materials in forced convection heat transfer has been extensively studied due to their potential applications in areas such as electronic cooling, drying processes, solid matrix heat exchangers, heat pipes, nuclear reactors, and the enhanced recovery of petroleum reservoirs. In nuclear reactors, porous media play a crucial role, where heavy water (D2O) flows through Uranium fuel rods. Here, heavy water acts as a coolant, extracting heat from the Uranium fuel rods, which serve as the porous medium. This porous medium effect enhances the cooling efficiency of nuclear reactors. The use of porous materials improves heat transfer through (i) flow redistribution, (ii) thermal conductivity modification, and (iii) enhancement of radiative heat transfer, thereby making them valuable in heat exchangers.

Literature review

Heat exchangers play a crucial role in modern chemical processes, significantly impacting the total assets involved in these processes [1]. As heat exchangers account for roughly half of the equipment used in such processes, improving their efficiency is paramount for energy conservation. One of the most effective ways to enhance heat exchanger performance is by improving the heat transfer coefficient between the fluid and the pipe wall. This can be achieved by increasing the flow velocity near the wall or reducing the boundary layer thickness to create a larger temperature gradient. However, in fully developed pipe flow, merely increasing fluid velocity has limited impact on radial temperature gradient changes near the pipe wall. Therefore, innovative heat transfer enhancement technologies have been developed [2]. Porous substrates are widely recognized for their high thermal conductivity and are extensively used to enhance heat transfer in various engineering applications. Research on convective heat transfer in porous media has gained significant attention, with numerous theoretical and experimental investigations reported in the literature [3]. Mahjoob and Vafai [4] conducted a comprehensive analytical study on forced convection through a generic channel subjected to a constant heat flux. They provided 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 annulus 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 used to study convective heat transfer in porous media. Alkam [8] numerically investigated forced convection flow in annuli partially filled with porous media, revealing that the Nusselt number increased under these conditions. Mohamad explored steady and laminar flow in conduits fully or partially filled with porous layers under different temperature boundary conditions, concluding that heat transfer enhancement was achievable with partially filled porous media.

Bhargavi et al. [9] studied the effect of porous media on heat transfer in fully developed flow through channels partially filled with porous media. They found that increasing the porous thickness above a certain value enhanced the Nusselt number on the fluid side more than it reduced it on the porous side. Satyamurty[10] investigated forced convection in thermally developing regions of channels partially filled with porous media, identifying the optimal porous thickness for maximum Nusselt number.
L. Rong et al. [11] in their study investigated the impact of porous media on heat transfer enhancement in a pipe using numerical simulations. They found 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.

Wentao Yan, Xin Yang, Tengqing Liu & Shuangfeng Wang [12] did the numerical simulation of heat transfer performance for ultra-thin flat heat Pipe.The heat transfer performance of ultra-thin flat heat pipes with copper mesh wick was studied by numerical simulation for different heating powers. The length, width and height of the ultra-thin flat heat pipe are 80 mm, 8.5 mm and 1 mm, respectively. The temperature distribution and flow characteristics of ultra-thin flat heat pipes were simulated by coupling porous media model and user-defined function in FLUENT. To validate the accuracy of the numerical model, the simulation results of the ultra-thin flat heat pipe are compared with the experimental data in predicting the evaporation section temperature. The numerical model has good accuracy for the one-dimensional heat transfer method of ultra-thin flat heat pipes. The velocity, pressure drop of the wick and total temperature difference have the same variation trend. With the increase of heating power, the temperature difference of ultra-thin flat heat pipes increases, and the pressure drop and the liquid velocity in the wick also increase.

Theory

The study of convective heat transfer in pipe flow, particularly with the inclusion of porous media, involves several fundamental governing equations that describe the continuity, momentum, and heat transfer processes. They are described in this section.

Continuity Equation

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

$$\frac{\partial(\rho \mathrm{u_x})}{\partial \mathrm{x}}+\frac{1}{\mathrm{r}}\frac{\partial(\mathrm{r}\rho \mathrm{u_r})}{\partial \mathrm{r}}=0 \tag{1}$$

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

Momentum Equations

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

$$\frac{\partial(\rho u_x)}{\partial t}+\frac{1}{\epsilon}\frac{\partial(\rho u_x u_x)}{\partial x}+\frac{1}{r\epsilon}\frac{\partial(r\rho u_x u_r)}{\partial r}=-\frac{\partial(\epsilon p)}{\partial x}+$$

$$\frac{\partial(\rho u_r)}{\partial t}+\frac{1}{\epsilon}\frac{\partial(\rho u_x u_r)}{\partial x}+\frac{1}{r\epsilon}\frac{\partial(r\rho u_r u_r)}{\partial r}=-\frac{\partial(\epsilon p)}{\partial r}+\mu_{\mathrm{eff}}\left(\frac{\partial^2 u_r}{\partial x^2}+\right.$$

Where, p is the pressure in $\mathrm{N/m2}$, μ_{eff} is the effective viscosity in $\mathrm{Ns/m2}$, 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.

Energy Equation

The heat transfer equation is given by,

$$\frac{\partial T}{\partial t}+u_x\frac{\partial T}{\partial x}+u_r\frac{\partial T}{\partial r}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right) \tag{4}$$

where, T is the temperature in K, α is the thermal diffusivity in $\mathrm{m2/s}$.

Body Forces in Porous Media

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

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

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

Numerical Method

The study presented here considers the thermal flow in a pipe partially filled with a porous medium simulated in ANSYS Fluent 2021. The computational domain for the porous medium and the pipe is give in Fig. 1. The porous medium is assumed to be homogeneous, isotropic, and saturated with a single-phase fluid in local equilibrium with the solid. The porous medium of radius Ri of 0.6R, 0.4R and 0.2 R , were R is the pipe inner radius, were studied. The length of the pipe is chosen to be 15 times the pipe's inner radius to ensure fully developed conditions at the exit. The region of porous insert is of length 200 mm. The walls of the pipe in the porous region is subjected to a constant temperature boundary condition with $\mathrm{T_w}=400\ \mathrm{K}$.

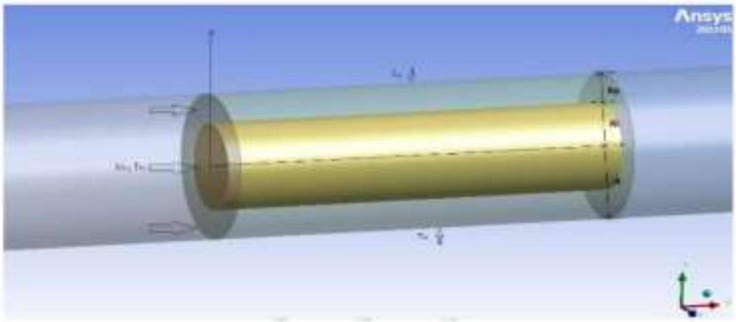

Fig. 1. Computational domain with schematics

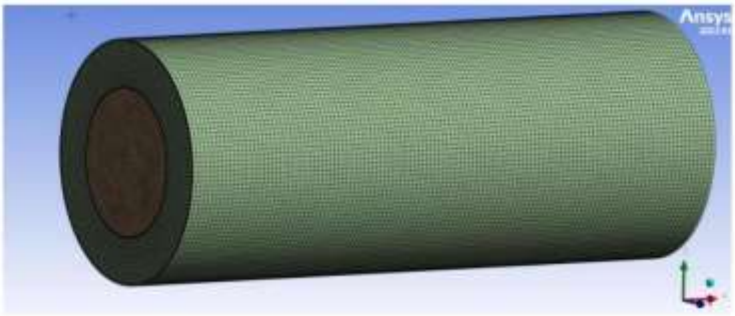

Fig. 2. Mesh on porous insert domain

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

VALIDATION

The numerical study is validated with the study of F. Rong et al. [11]. The flow condition of $\mathrm{Ri} = 0.6; \epsilon = 0{:}6$; Prandlt number, $\mathrm{Pr} = 0{:}7$ and Reynolds number, $\mathrm{Re} = 100$ is simulated and found to be with in 5% error of the analytical study presented in [11]. Fig. 3 compares the result of velocity ux vs R for the above condition.

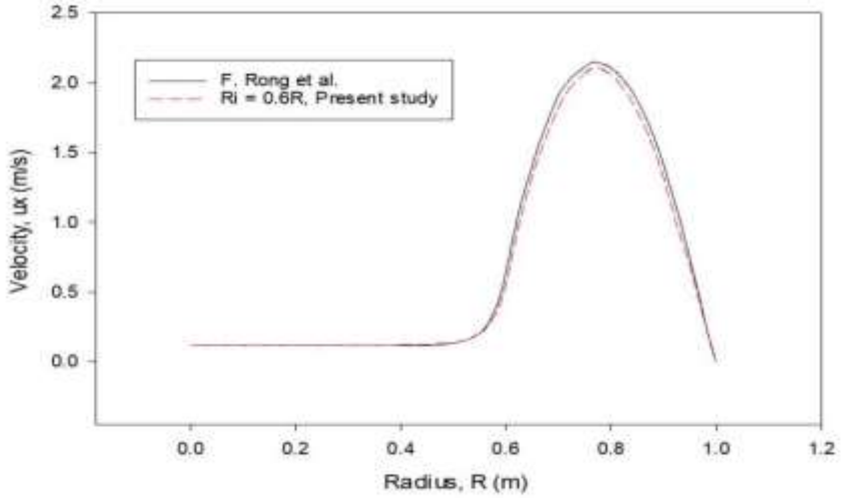

Fig. 3. Validation study

RESULTS

Presented below are the results of the study for flow condition of Ri $= 0.6; \epsilon = 0{:}6;$ Pr $= 0{:}7$ and Re $=$ 100.The velocity, and temperature contours in the XY plane through the centreline of the pipe are illustrated in Fig. 4 and Fig. 5 respectively. The velocity contours reveal an increase in velocity in the annular region between the pipe wall and the porous insert due to area reduction. This phenomenon is indicative of the enhanced flow dynamics caused by the presence of the porous media. The temperature contours highlight the significant impact of the porous layer on heat transfer, demonstrating that the porous region effectively enhances thermal conductivity and aids in heat transfer. These visualizations underscore the importance of optimizing porous media characteristics to improve overall system performance.

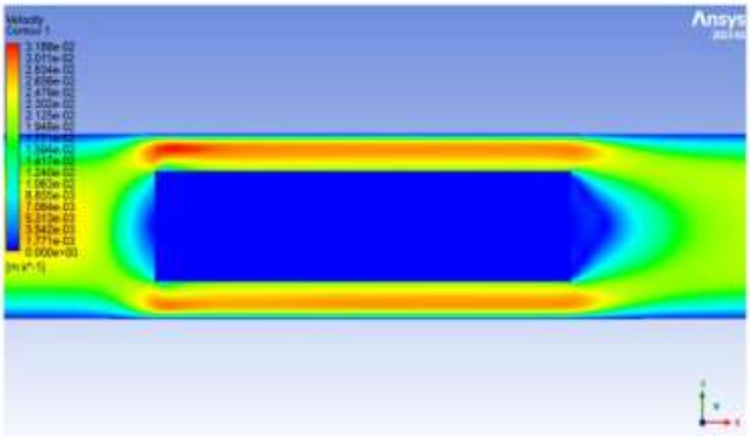

Fig. 4. Velocity contour in the diametrical XY plane

The Fig. 7 and Fig. 8 presents the results of the study for flow condition and Nusselt number distribution respectively for Ri $= 0.6, 0.4, 0.2$ and 0.0 (no porous insert); $\epsilon = 0{:}6;$ Pr $= 0{:}7$ and Re $= 100$.

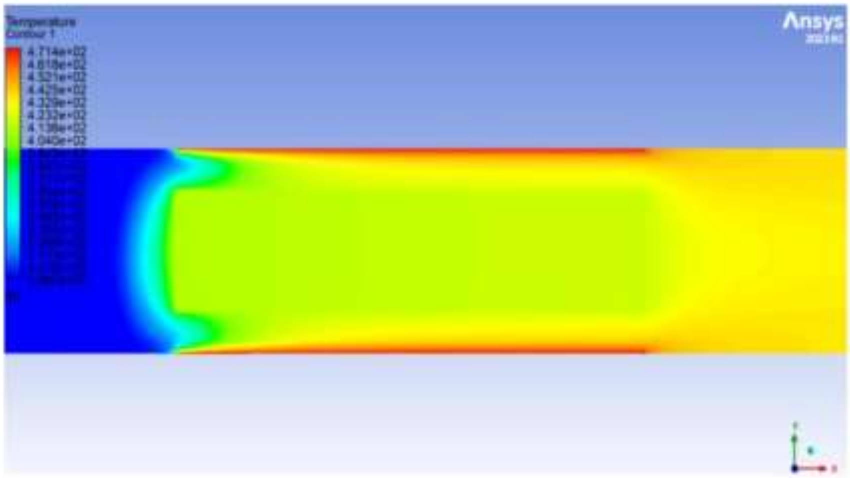

Fig. 5. Temperature contour in the diametrical XY plane

As the porous media thickness increases, the peak axial velocity also increases and shifts closer to the pipe wall. However, the peak value does not always continue to increase; it becomes constant when the pipe is completely filled with porous media or when the porous medium thickness is very close to the pipe diameter. The overall conduction efficiency increases, and the temperature distribution becomes more uniform with the insertion of porous media. A significant temperature gradient appears near the pipe wall, greatly enhancing the heat transfer effect. Both 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 convection heat transfer. The maximum heat transfer intensity with porous media can be nearly three times that of a blank pipe. Inserting porous media into the pipe center leads to increased fluid velocity and improved heat exchange between the fluid and the pipe wall. Without porous media, most heat concentrates in the pipe center, resulting in poor heat transfer on the pipe wall. With porous media, the heat distribution becomes more uniform.

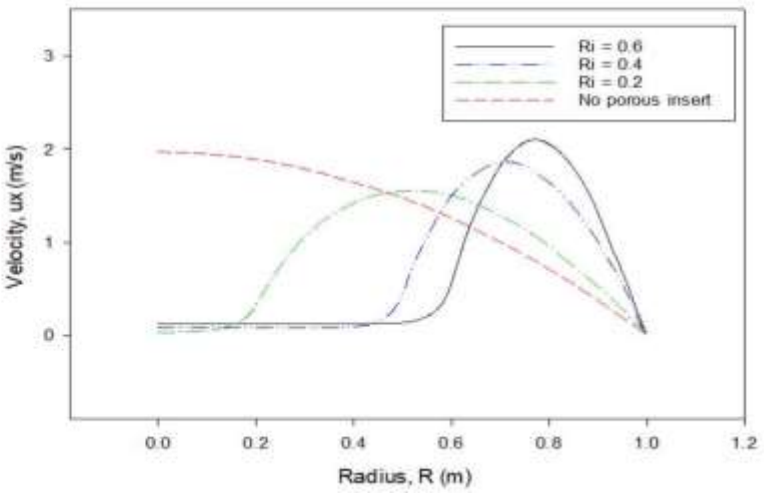

Fig. 6. Velocity vs. Radius for different Radius, Ri

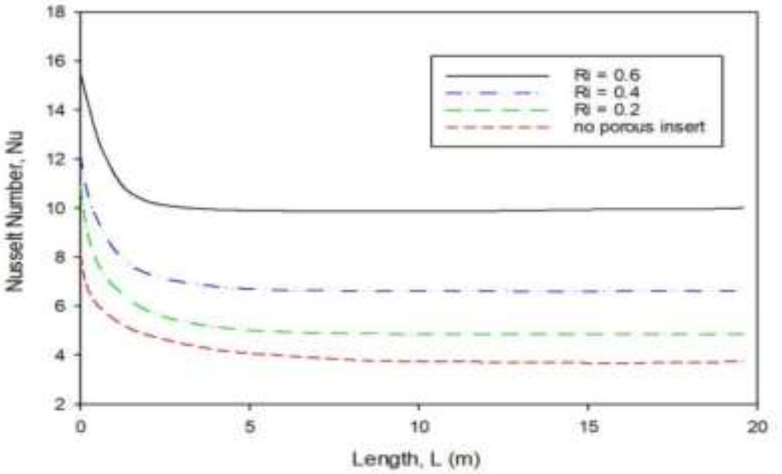

Fig. 7. Nusselt number distribution along porous media length

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 ($\epsilon = 0.6, \mathrm{Re} = 100$, and $\mathrm{Pr} = 0.7$. 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 blank pipe.

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