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REVIEW OF LAMINAR FORCED CONVECTION IN DIFFERENT SHAPE CHANNEL WITH NANOFLUID SUOERPOSED IN POROU MEDIA

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ABSTRACT

Since industrial and microchannel fluid flow applications are intimately tied to the energy sector, forced convection heat transfer is one of the most often employed heat exchange methods in many thermal devices. The porous media (P.M) help to provide a vast surface area that may be utilized in a variety of applications, so its play a significant role in improving convective heat transmission inside channels containing fluid flow. On the other hand, fluids with nanoparticles could greatly increase heat conductivity. Thus, the thermal performance of forced convection systems within channels can be greatly enhanced by the combination of porous materials with nanofluids. Studies on convective heat transmission through nanofluids are covered in this article, with particular attention to the defiance associated with the use of Porous media. The coefficient of heat transmission can be improved by adding a porous medium to the channels, according to some study, while other studies have found that nanofluids overpass a higher volumes traditional fluids. Additionally, a number of studies have looked at how the flow region's geometry within forced convection channels affects heat transfer efficiency.

Keywords: Porous media, Channel, Forced convection, Nanofluid.

NOMENCLATURE

D	Diameter of circular cylinder (m)
Da	Darcy number
Re	Reynold number
X	Cartesian coordinate in horizontal dir (m)
Y	Cartesian coordinate in vertical dir (m)
U	Velocity in x- dir (m/s)
V	Velocity in y-dir (m/s)
T	Temperature
t	Time
P	Pressure pa

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Pr	Prandtl number
F1	Volume force of porous media in x-dir
F2	Volume force of porous media in y-dir
Yc	Position of the circular cylinder
θ	Dimensionless temperature
φ	Volume fraction of nanofluid
ψ	Stream function
U(p/n)	Dimensionless velocity of porous/nanofluid in x-dir
V(p/n)	Dimensionless velocity of porous/nanofluid in y-dir

INTRODUCTION

There is a growing need to develop advanced, highly efficient cooling technologies to meet the demands of modern thermal applications, with a focus on improving heat transfer and reducing frictional losses. These technologies encompass a wide range of cooling methods, divided between passive and active systems. Among the strategies used to enhance heat transfer efficiency, the application of flow-responsive (P.M) is a promising solution (Rezaie, Rosen, 2012). These media excellent at enhancing the required cooling process due to the presence of pores in their hydrodynamic structure. In other words, they have a relatively high surface-to-volume ratio compared to other materials, along with their ability to achieve a high level of mixing of the fluids flowing through them (Nkurikiyimfura, Wang, 2013 and Laohalertdecha, Naphon, Wongwises, 2007). Furthermore, another efficient way to enhance thermal performance is to use the forced fluid pulsation approach at the channel inlet. The fluid layer's consequent hydrodynamic weakness greatly enhances vertical convective heat transfer over hot surfaces by supertastering flow blending (Al-Sumaily, Thompson, 2013).

Adding fins, altering the cross-sectional forms of tubes, and using twisted ribbons are just a few examples of passive heat transfer increases. Because of its promising potential and the favorable outcomes shown by several studies, the use of P.M has garnered the most attention from researchers among these choices (Al-Salem, Oztop, Kiwan 2011 and Pop, Ingham, 2001 and Bejan, Dincer, Lorente, Miguel, Reis 2000 and Hamdan, Al-Nimr, Alkam, 2004). The two primary categories of forced flow in channels are forced flow with conventional or nanofluids and forced flow with fully or partially (P.M) applied. Both active and passive techniques can be applied to enhance the process, as shown in figure 1. Although active techniques, such the use of nanofluids, greatly improve heat transfer efficiency, they come with additional costs, such as raising the heat exchange medium's heat capacity or supplying more mechanical energy. On the other hand, passive techniques, like the application of (P.M), enhance heat transmission without incurring extra expenses, albeit they may necessitate slight adjustments to the heat exchanger's design.

Forced convection heat transfer is gaining significant importance when using (P.M), as it finds widespread application in many fields, such as solid-state heat exchangers, packed bed reactors (Fathiganjehlou, Eghbalmanesh, Baltussen, Peters, Buist, 2023 and Al-Raoush, Willson, 2005 and Al-Raoush, Thompson, Willson, 2003 and packed bed generators Lu, Xie, Ingham, Ma, Pourkashanian, 2018), catalytic, fixed-bed nuclear propulsion systems (Al-Sumaily, Nakayama, Sheridan, Thompson, 2012) and chemical particle carrier media (Shanglin Liu, Xu, Lu, Wang, Liu, Wang 2024 and Mughari, Naseh, Noori) 2025 porous media are an effective means of enhancing heat transfer.

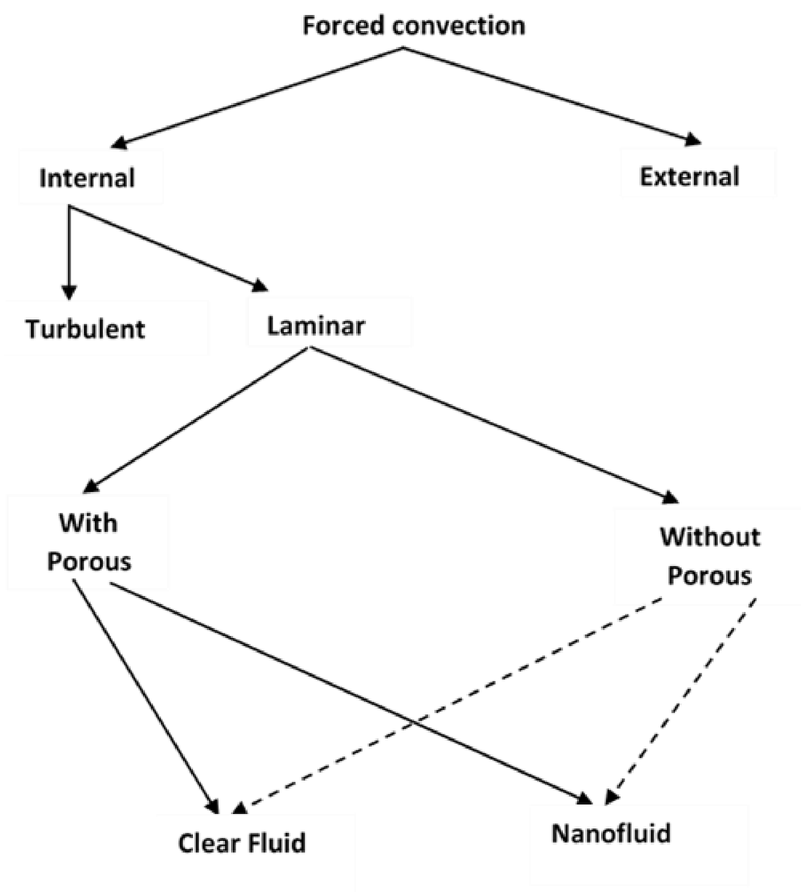
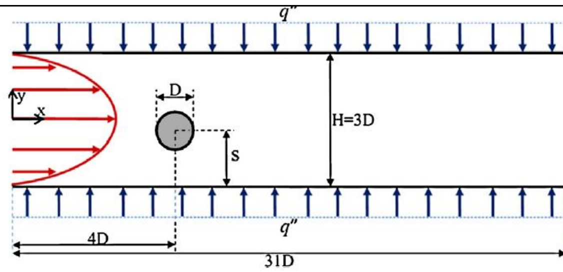
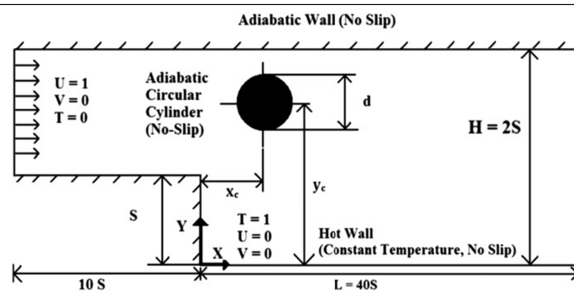
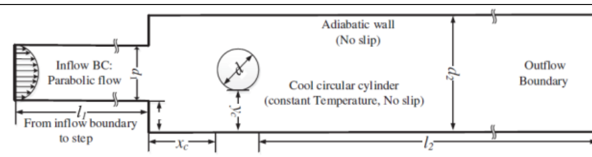
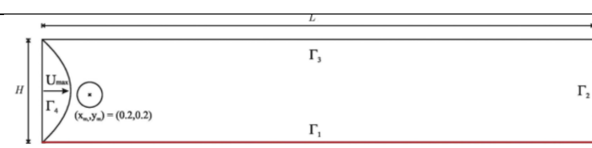
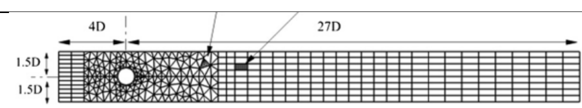
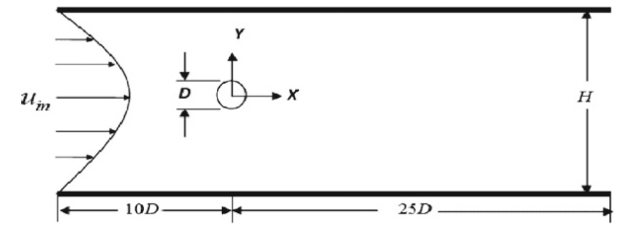
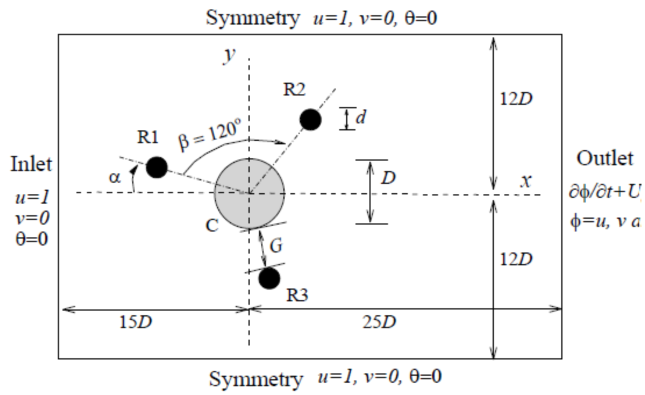
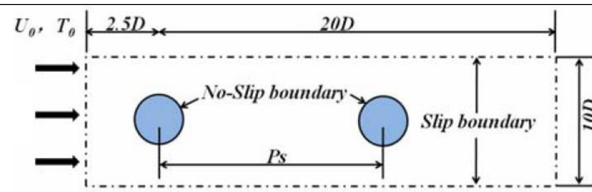
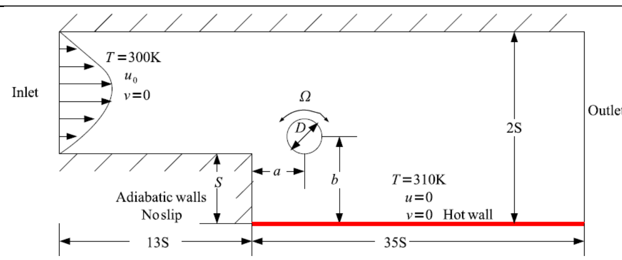
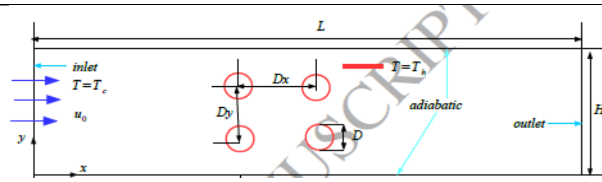


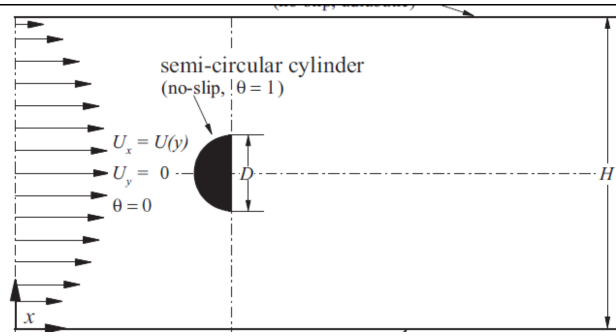
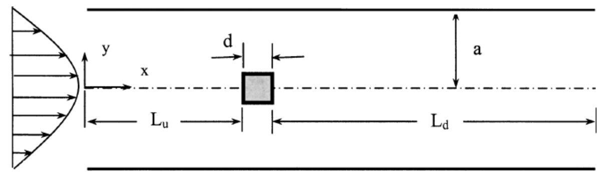
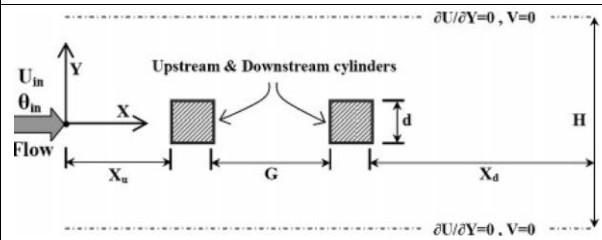
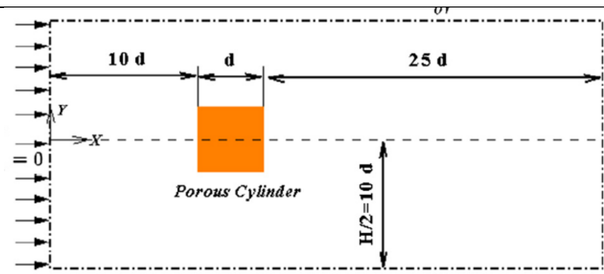
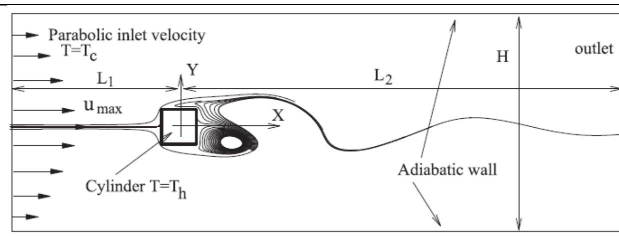
Fig. (1) Classification of Forced convection flow in channels

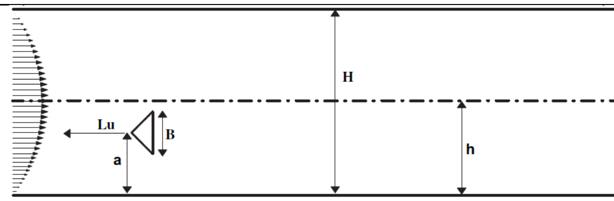
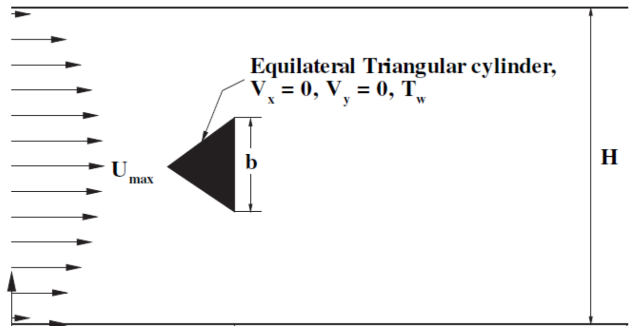
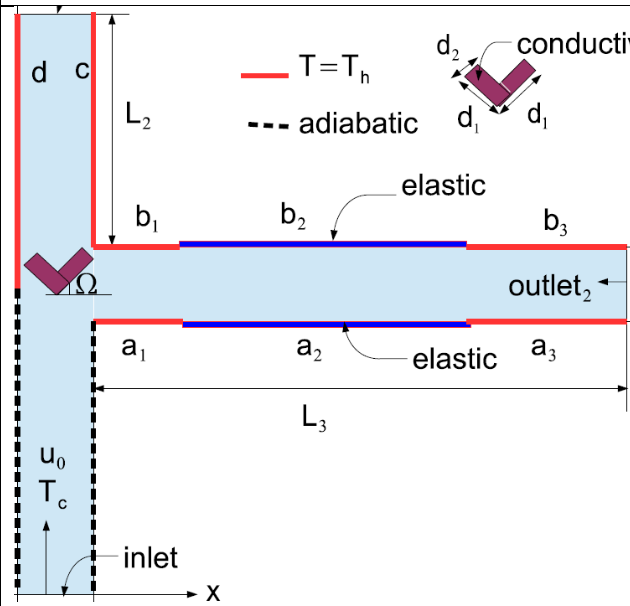
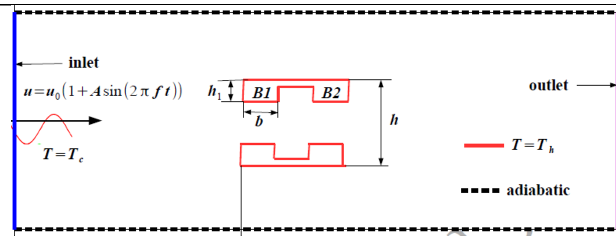
Convective heat transfer efficiency is increased by porous structures because they increase the contact surface area and improve fluid interpenetration (Gazy, Akira,Sheridan, Thompson 2012). Without going into the specifics of the thermophysical properties, the main focus of this work will be a thorough review of research on forced convection in channels with and without porous media, as well as the impact of adding PM. Furthermore, this evaluation will offer a useful framework for further investigation (see Table.1).

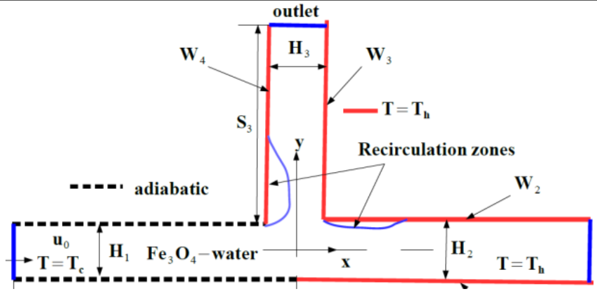
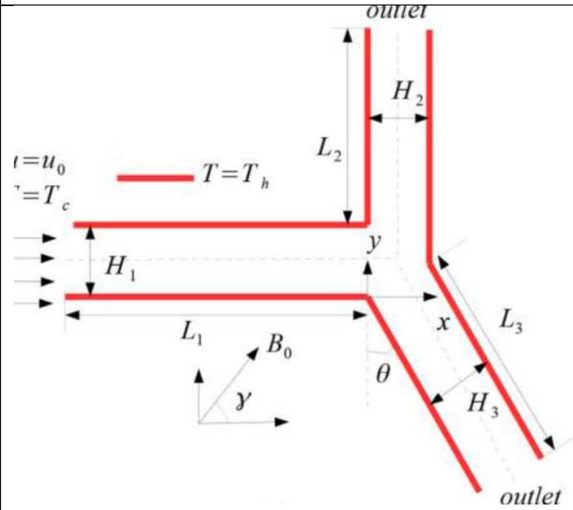
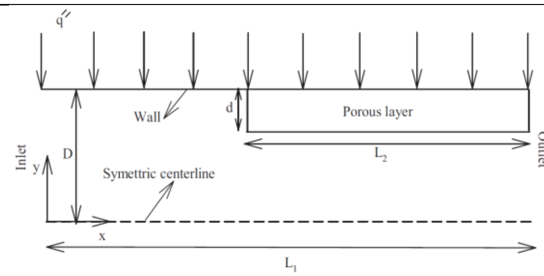
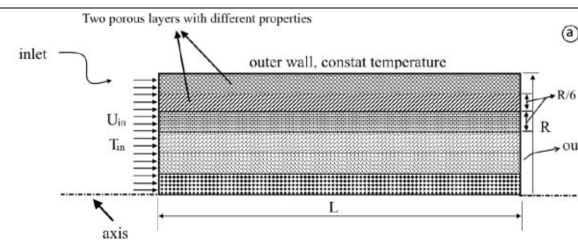
Table 1. Various shapes of previous studies that addressed the subject of fluid flow within channels.

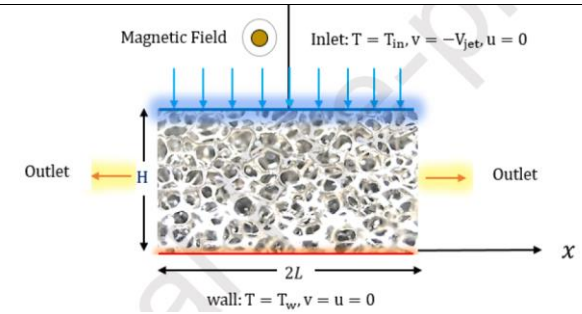
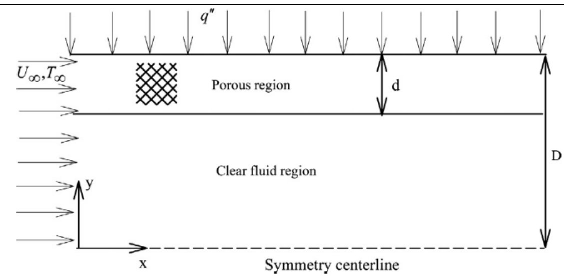
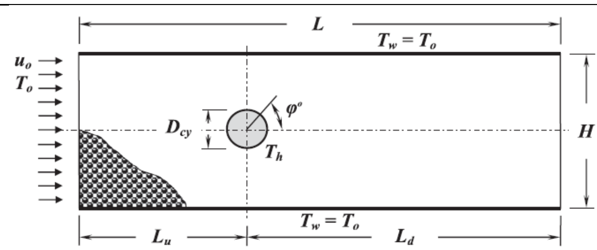
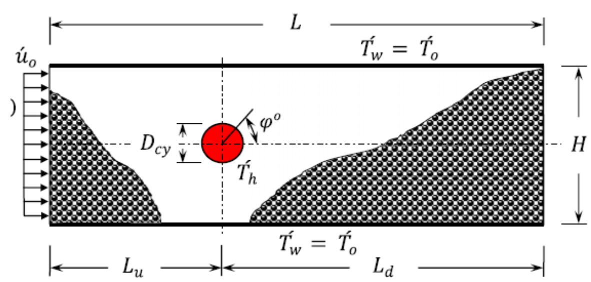
Seq.	Type of fluid	Reynold number range	Prandtl number range	Geometry
1	Different fluid	100	0.1 -10	
2	Air	1-200	0.7	
3	Air	10-300	0.7	
4	Nanofluid	10-200	7.3	
5	Different fluid	100	0.1-10	

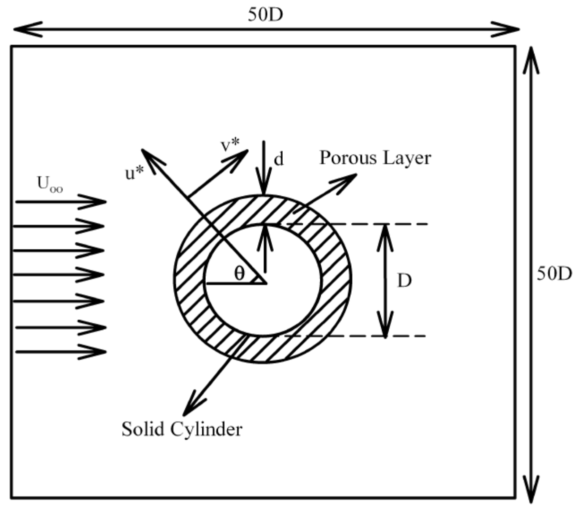
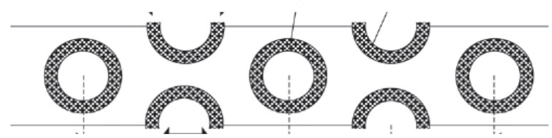
6	Water	45-250	7.3	
7	Air and water	200	0.7 and 7	
8	Air	200	0.7	
9	Water	10-200	6.9	
10	CuO-water nanofluid	100-1000	7.3	

11	Different fluid	50-200	0.7, 10, 100	
12	Air	*10-200*	0.7	
13	Air	1-200	0.7	
14	Air	70–150	0.7	
15	Air	1-250	0.7	

16	Air	100-450	0.71	
17	Air	1-80	0.71	
18	Water	100 - 500	6.9	
19	Water/ nanofluid	100-500	6.9	

20	Water/ nanofluid	100-500	6.9	
21	Water/ nanofluid	100-500	6.9	
22	Porous/ fluid	100	6.9	
23	Porous/ Nanofluid	1000	7.2	

24	Porous/ Nanofluid	50 - 500	7.1	
25	Porous/ fluid	1 - 100	6.9	
26	Porous/ fluid	1–250	7	
27	Porous/ fluid	1–250	7.1	

28	Porous/ fluid	1–40	7.2	
29	Porous/ fluid	50-400	0.71	

Mathematical model

The flow is steady, two-dimensional, incompressible, and laminar. The walls of the channel and cylinder are impermeable, i.e., they do not allow slippage, while the inlet and outlet zones, as well as the interface between the two zones, are permeable. (P.M) have homogeneous and isotropic permeability. The Darcy-Brinkman model is used to analyze and predict the flow behavior within (P.M). Accordingly, the continuity, momentum, and energy equations are represented in their dimensionless form in this work using the equation shown below.

Continuity equation

$$\frac{\partial U_{p/n}}{\partial X}+\frac{\partial V_{p/n}}{\partial Y}=0 \qquad (1)$$

Momentum equation

$$U_{p/n}\frac{\partial U_{p/n}}{\partial X}+V_{p/n}\frac{\partial U_{p/n}}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{Re}\left(\frac{\partial^2 U_{\frac{p}{n}}}{\partial X^2}+\frac{\partial^2 U_{\frac{p}{n}}}{\partial Y^2}\right)+F1 \qquad (2)$$

$$U_{p/n}\frac{\partial V_{p/n}}{\partial X}+V_{p/n}\frac{\partial V_{p/n}}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{Re}\left(\frac{\partial^2 V_{\frac{p}{n}}}{\partial X^2}+\frac{\partial^2 V_{\frac{p}{n}}}{\partial Y^2}\right)+F2 \qquad (3)$$

Energy equation

$$U_{p/n}\frac{\partial\theta_{p/n}}{\partial X}+V_{p/n}\frac{\partial\theta_{p/n}}{\partial Y}=\left(\frac{\partial^2\theta_{p/n}}{\partial X^2}+\frac{\partial^2\theta_{p/n}}{\partial Y^2}\right)*(Re\,\mathrm{Pr})^{-1} \quad (4)$$

Where the subscript (*p/n*) refers to the properties of the (P.M) and nanofluid, and F1 and F2 equal zero for pure fluid while for (P.M) its equivalent as:

$$F1=-\frac{U_{p/n}}{(Re\,Da)} \quad (5)$$

$$F2=-\frac{V_{p/n}}{(Re\,Da)} \quad (6)$$

SIMULATION STUDY

Channels without a porous medium

The initial discussion addresses the use of conventional or nano-fluids within channels, as well as the classification of existing studies based on the shape of the inner cylinder of the channel, such as circular, triangular, square, etc. In this context, (Cheraghi, Raisee, Moghaddami, 2003) conducted a numerical study on a microchannel containing a homogeneous hot hole and an inner surface insulated by a circular cylinder. The study's main objective was to examine how the distance between the bottom wall and the cylinder affected the pressure drop and heat transfer rates across the wall surfaces. The findings demonstrated that, in contrast to the properties of a flat channel, heat transfer was better in the advanced convective flow region within the channel. As shown in figure 2, which shows the vortex field distribution and channel temperature, the greatest heat transfer enhancement was noted when the circular cylinder was positioned in the center of the channel.

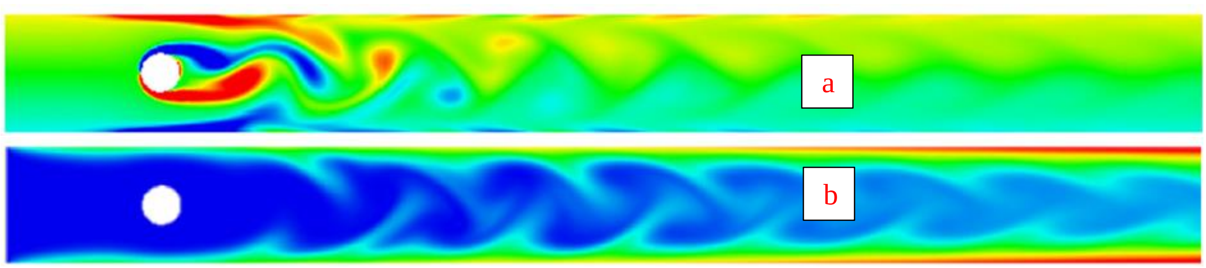


Fig. 2. The vortices (a) and temperature contour (b) for the fluid flow in the channel (Cheraghi, Raisee, Moghaddami, 2003).

Additionally, (Kumar and Dhiman, 2012) used a thermally insulated circular cylinder to perform an analytical investigation on forced laminar backflow in a two-dimensional channel. Figure 3 illustrates how the use of a circular cylinder significantly improved the greatest Nusselt number value by up to 155% as compared to the unconfined (cylinder-free) scenario. Some studies investigated the flow around a circular cylinder in many channel geometry, such that (Wang, Rees, Pop, 2004) presented this state in a suddenly expanding channel using a numerical simulation in a similar setting. Their findings demonstrated that the Reynolds number has a major impact on the dynamics of heat transfer, with the time-averaged Nusselt number rising as the Reynolds number increases. However, in order to enhance the fluid motion and heat transfer properties in a back-graded geometry with a spinning cylinder, (Hussein, Jamalc, Ahmedd, 2019) carried out a numerical analysis. The findings demonstrated that the isotherms in the channel were uniformly distributed at low Reynolds number values, suggesting a decreased rate of heat transmission. The isotherms were seen to progressively move towards the bottom wall as the Reynolds number increase, as shown in figure 4. By altering frequency impacts, (Beskok, Raisee, Celik, Yagiz, Cheraghi, 2012)subsequently accomplished notable advancements in heat transfer by carrying out methodical investigations to comprehend the impact of rotation angle and frequency on heat transfer processes. Numerical solutions of the two-dimensional, unstable Navier-Stokes equations for incompressible fluids served as the foundation for all simulation results. However, (Singha and Sinhamahapatra, 2010) used a finite-volume technique with an unstructured mesh based on the initial variables formulation to study fluid flow around a circular cylinder placed at the center of a channel. According to their findings, the interaction between the vortices produced by the cylinder and the channel walls delays the transition of the vortex shedding phase when the channel walls are near the cylinder.

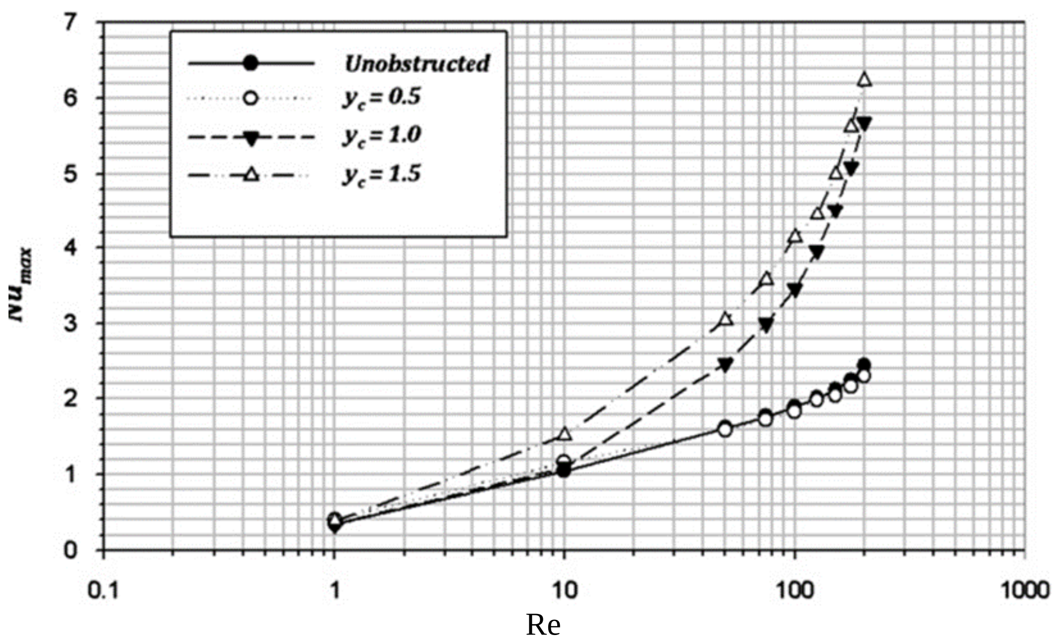


Fig. 3. Distribution of heat transfer characteristics with Reynold number and max Nu (Kumar and Dhiman, 2012).

A numerical investigation of fluid flow and forced convection heat transfer in a laminar flow system was carried out by (Harimi, Marjani, Moradi, 2016). The mesh interference approach was used to simulate the system, which was a circular cylinder encircled by three control rods. The Prandtl number ranged from 0.7 for air to 7.0 for water, and the study concentrated on unsteady flows with Reynolds numbers between 200 and 7.0. To comprehend the features of the heat flow and fluid motion around the main cylinder and its surrounding rods, the researchers used both local and intermediate Nusselt values. The researchers found that the variation in heat transfer rate with angular displacement of the master cylinder showed a significant difference when compared to small rods, with respect to the Nusselt number around the master cylinder. They also observed a significant decrease in the average Nusselt number of the master cylinder, a trend that became more pronounced with decreasing spacing ratios. Conversely, they observed an increase in the Nusselt number with increasing spacing ratios.

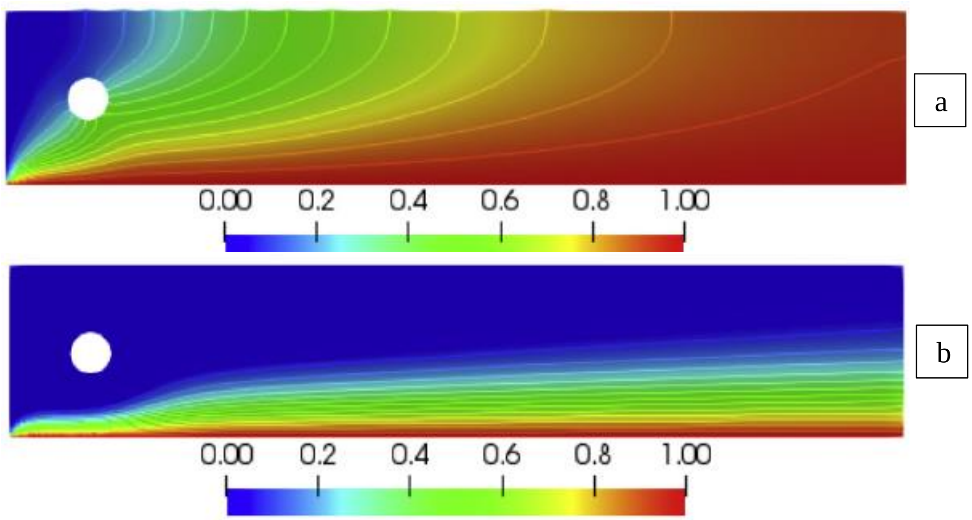


Fig. 4. the temperature distribution in a channel at (a) Re=10 and (b) Re=200, (Hussein, Jamalc, Ahmedd, 2019).

(Zhou, Xi, 2016) performed numerical simulations to investigate the forced convection heat transfer between several series circular cylinders and used a sophisticated code based on the finite volume method and the complex grid system. The research concluded that vortex stability and velocity recovery significantly affect the improvement of forced convection heat transfer. Several methods were used to display the numerical data, such as streamlines, isothermal curves, and graphs that highlighted the key values under analysis. Where a numerical study is concentrated on the effects of Reynolds number, cylinder angular velocity, and nanoparticle volume fraction according to these findings, the fluid flows over the cylinder when it rotates clockwise, as shown in figure 5, and the opposite pattern happens when the cylinder rotates counterclockwise. The effect of forced convection of a nanofluid around a group of circular cylinders inside a channel exposed to the influence of a uniform magnetic field has been investigated numerically by by (Selimefendigil and Oztop, 2014) using the same framework. Using the finite element method, the simulation maintained a constant temperature for each of the four circular cylinders stacked in a row.

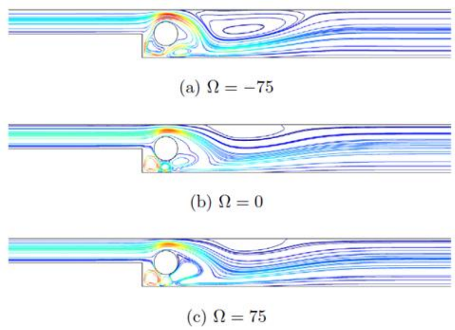


Fig. 5. exhibit the score of the streamlines for the angle of cylinder rotation at different Re numbers, (Selimefendigil and Oztop, 2014).

It was found that when the Hartmann number increased, the stable secondary peaks of the local Nusselt number over the heated surface steadily decreased until they vanished entirely when the maximum value of this number was attained. However, in an unstable dynamic system, (Kumar, Dhiman, Baranyi, 2016) investigated the fluid flow and heat transfer properties surrounding a semicircular cylinder positioned inside a confined channel. The impact of several control factors, including the Reynolds and Prandtl numbers, was examined in this work using a two-dimensional simulation. The findings showed how the Prandtl number clearly affects changing the values of the Nusselt number, as shown in detail in figure 6. Numerous physical phenomena pertaining to flow and heat transmission have been studies on square bodies in channels such as in papers. (Rahnama and Moghadam, 2005) study included a numerical analysis of unsteady laminar flow around a heated square cylinder.

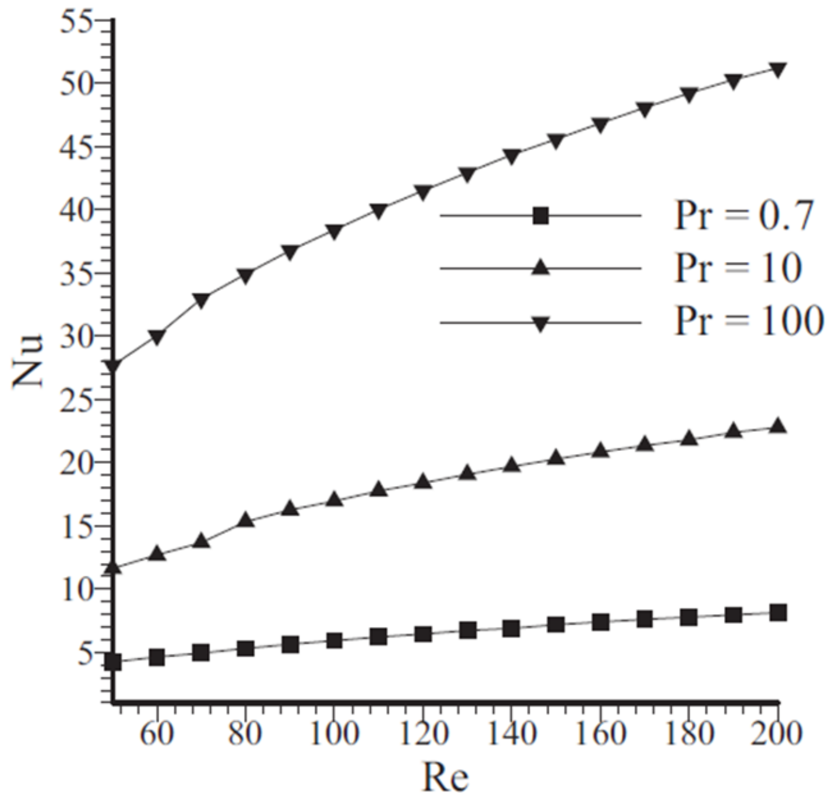


Fig. 6. Show the relationship between the average Nusselt number and Reynold number at different Prandtl number, (Kumar, Dhiman, Baranyi, 2016).

As the primary parameter for system analysis, the Reynolds number is determined by the cylinder chord length and the average flow velocity. The results show that in unsteady flow, where vortices form behind the cylinder body, a higher Reynolds number leads to a higher Nusselt number. In a different research, (Sohankar and Etminan, 2009) investigated the heat transfer and flow characteristics between two identical square cylinders. In order to gain a better understanding of the thermodynamic behavior of these systems, this study includes streamlines, isotherms, instantaneous and mean vorticity patterns, and a range of Reynolds numbers.

On the other hand, (Suhankar, Khodadadi, Rangraz, 2015) investigated the effects of uniform suction and blowing on the surfaces of a square cylinder. The researchers found the wake region and vortex shedding over a range of Reynolds numbers from 60 to 160 and a Prandtl number of 0.72. The study found that the best heat transfer conditions are achieved when suction is applied to all surfaces of the cylinder. The main topic of (Rashidi and Esfahani, 2015) was the study of forced convection heat transfer in a channel with an integrated square barrier. Their results demonstrated the dual effect of barriers and walls on the thermodynamics of the flow by proving that the presence of channel walls reduces the effect of the magnetic field on the Nusselt number.

Regarding triangular cylinders and their effect on fluid flow and heat transfer in horizontal channels, (Farhadi Sedighi, Korayem, 2015) performed a numerical evaluation of how the proximity of a triangular cylinder to the wall affects the flow lines and isotherms. According to their results, the proximity of the cylinder to the wall reduces vortex shedding, which significantly reduces the heat transfer rate (represented by the mean Nusselt number) at low Reynolds numbers. (Srikanth, Dhiman, Bijjam, 2010) investigated heat transfer and fluid flow around a long, equilateral triangular cylinder in a horizontal channel over a range of Reynolds numbers from 1 to 80, with a Pr value of 0.71. According to the study, as the Reynolds number increases, the average Nusselt number and the length of the wake region also increase, indicating the influence of the Reynolds number on heat transfer and distribution. However, due to their numerous real-world applications, branched channels are a prominent area of interest in this discipline. For example, forced convection under the influence of a magnetic field was studied in a branched channel containing a nanofluid with water at normal conditions. (Selimefendigil, Oztop, 2019) also studied the function of an L-shaped conductive barrier in controlling the flow lines in a branched channel with partially elastic walls exposed to a magnetic field. According to the results, the size, orientation, and design of the baffle significantly affect the distribution of flow areas in the channel and the heat transfer rate, making it a useful control tool (see figure 7).

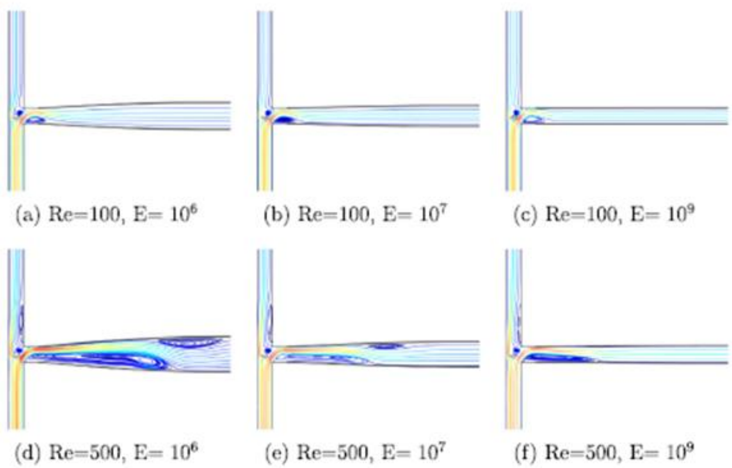


Fig. 7. Streamlines for different Reynolds number (Selimefendigil, Oztop, 2019).

Additionally, in a related study, some researchers investigated the pulsating forced convection of a nanofluid across a parallel corrugated surface containing magnetic fibers dispersed throughout. This case was analyzed numerically using the finite element method, specifically the Galrekin method, which yielded accurate and comprehensive insights into the influencing parameters (e.g., Reynolds number, volume fraction of nanofluids, and Prandtl number) on the thermal and hydrodynamic performance of these systems. The results showed that increasing the Reynolds number and volume fraction of solid nanoparticles enhances heat transfer, while increasing the ripple wave coefficients has a negative effect on heat transfer under steady flow conditions. (Selimefendigil, Oztop, Sheremet, Abu-Hamdeh, 2019) performed numerical simulations in the same setting using a residual finite element method based on the Galkin model. The study looked at how different Reynolds numbers (100–500) and volume fractions of nanoparticles (0–4%)

affected the parameters of convective heat transfer. The study came to the conclusion that the position and size of the recirculation zones that develop on the branching channel walls are significantly influenced by the Reynolds number.

Channels with Porous Media

Studies pertaining to the application of P.M in the above described channels are included in this part. PM helps to improve heat transfer while lowering pressure drop rates. Multilayered gradients (P.M.) with better characteristics and organization have been used by (Siavashi, Bahrami, Aminian, 2018) to improve heat transmission and lower pressure loss. The optimized design obtained a performance assessment factor of 0.845, according to the data. Additionally, under ideal circumstances, the thermal performance was approximately tripled by using a 5% alumina-water nanofluid. The heat transfer properties resulting from forced pulsing flow in a channel filled with a fluid-saturated (P.M) medium have been investigated numerically by (Kim, Kangs, Hyuni, 1993) in a different study.

They used the finite-volume method to solve the two-dimensional time-resolved control equations and the expanded Brinkmann-Forchheimer Darcy model. In order to enhance the thermal and hydraulic performance of porous heat exchangers, (Akar, Rashidi, Esfahani, 2017) suggested porous packing locations. According to their study's findings, lowering the horizontal porous layer's thickness from one unit to half reduced the pressure drop by 48% and the Nusselt number by 13%. Lastly, a model to investigate the flow of a water-and-alumina nanosystem inside a rectangular porous metal foam was presented by (Izadi Siavashi, Rasam, Xiong, 2019). As shown in figure 8, this system was exposed to an upward jet effect when the bottom wall was hot.

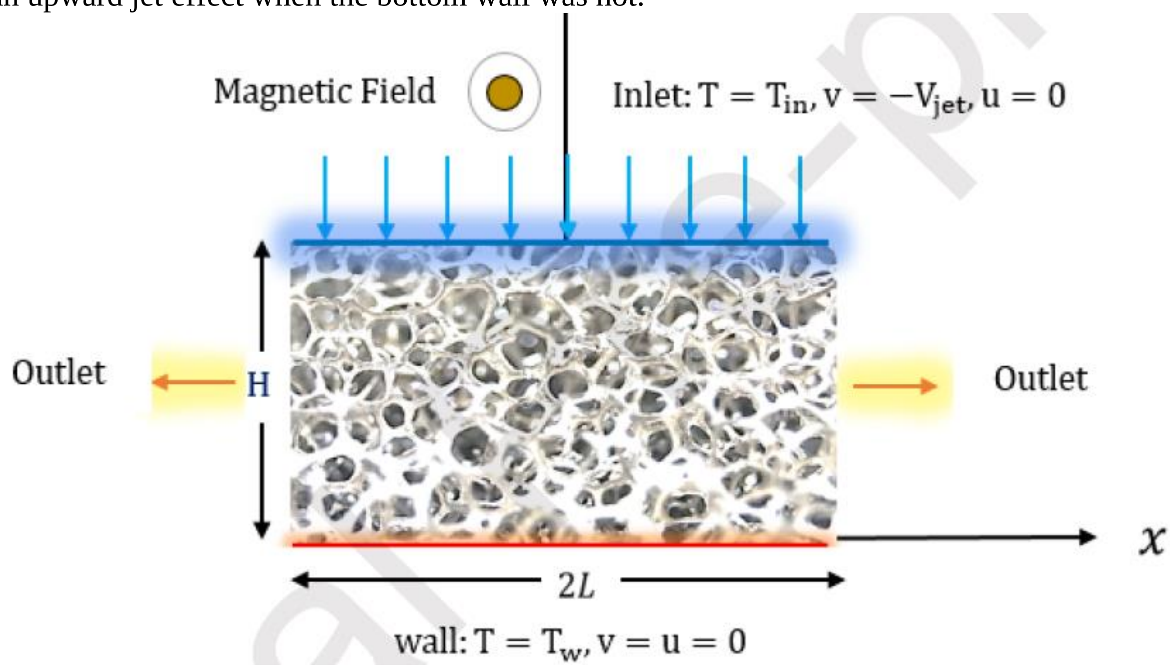


Fig. 8. Schematic of the studied porous metal (Izadi Siavashi, Rasam, Xiong, 2019).

The researchers discovered that at low porosity, the Nusselt number somewhat falls as the Hartmann number (Ha) increases, however at large porosity, the reverse pattern could be seen. On the other hand, the heat transfer in a porous solar heat exchanger is conducted by many studies. Where (Rashidi, Bovand, Esfahani, 2015) investigated radiative and convective heat transfer in a solar heat exchanger made of porous materials as shown in figure 9. Simulations at different Reynolds numbers (1-100) were used to accomplish this. They discovered that as the Darcy number rises, the pressure drop falls, reaching roughly 58% and 23% for d = 1/3 and 1, respectively. Additionally, by examining governing parameters such as Reynolds, Nusselt, Stewart, and Prandtl numbers, (Rashidi Dehghan, Ellahi, Riaz, Abad, 2014) examined heat transmission across square diamond-shaped porous barriers. Together with graphical depictions of flow velocity and thermal fields, as shown in figure 9 they also offered a physical explanation.

Given the porous materials many engineering uses, recent studies have emphasized the significance of investigating hot cylinders encircled by porous layers in many application (Wong, Rees, Pop, 2004, Chikh, Boumedien, Bouhadef, Lauriat, 1995, Ansari, Taghi, Naeeni, 2025, Sebty Al Zahrani, Kiwan, 2009). Here, (Rashidi, Tamayol, Valipour, Shokri, 2013) conducted a computational analysis of heat transport and flow around a cylinder encircled by a uniform layer of porous material. The findings demonstrated that the rebound zone's length increases with the presence of the porous layer, resulting in a decrease in the Darcy number and a rise in the critical radius of insulation. The impact of varying particle diameters in a layer of spherical particles around a closed circular cylinder (see figure 10) was also investigated numerically by (Al-Sumaili, Nakayama, Sheridan, Thompson, 2012). A broad range of Reynolds number values (1 to 250) were covered by the study.

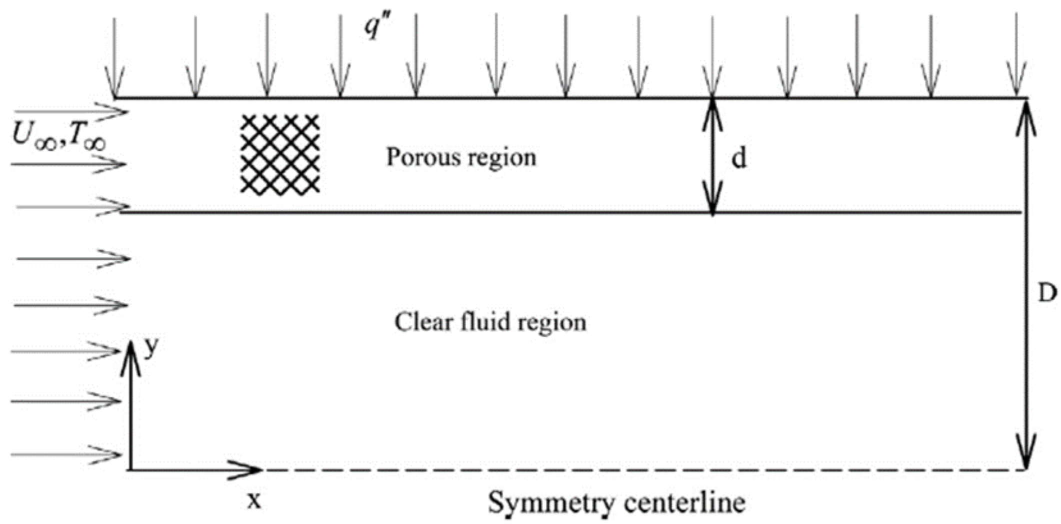


Fig. 9. The schematic of computational domain (Rashidi, Bovand, Esfahani, 2015).

In contrast to a channel without these materials, the study showed that adding porous materials surrounding the cylinder improves heat transfer overall. The results showed, in particular, that using a (P.M) with a high degree of porosity significantly improves heat transfer efficiency while reducing undesired pressure loss. In a different study, (Al-Sumaili, Sheridan, Thompson, 2012) used the methods depicted in figure (Raoush, Thompson, Willson, 2003) to investigate the heat transfer by dynamic forced convection from a circular cylinder positioned inside a horizontal layer. The local thermal imbalance theory served as the foundation for this investigation, which employed a numerical method based on the spectral element method to examine the phenomenon.

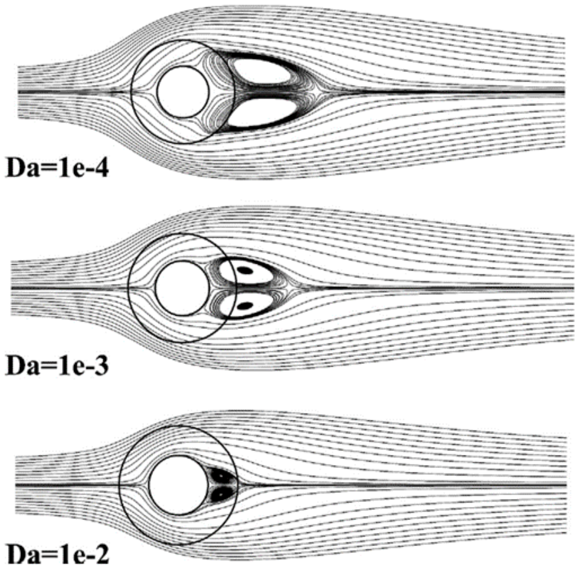
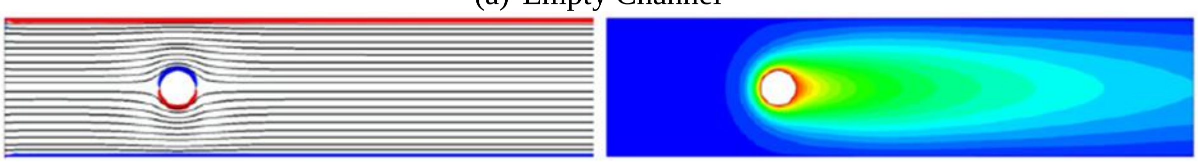


Fig. 10. Streamlines contour at different Da numbers and Re = 20, (Rashidi Dehghan, Ellahi, Riaz, Abad, 2014).

Studies conducted by researchers have demonstrated that the use of porous particles significantly increased the efficiency of heat transfer while reducing the dents behind the cylinder.

(a) Empty Channel



(b) Porous Channel

Fig. 11. The isotherms (right side) and vorticity with streamlines (left side) for empty channel (a) and porous channel (b) (Al- Sumaili, Sheridan, Thompson, 2012).

The impact of sinusoidal variable flow at a non-zero mean flow rate on heat transfer was investigated by (Al-Sumaili and Thompson, 2013). This flow happens through a circular cylinder that is positioned inside a channel that has a PM or an empty horizontal channel. When compared to pulsing flow, they showed that the application of P.M greatly improves heat transfer from the cylinder, particularly at high Reynolds numbers. The study conducted by (Alvandifar, Avval, Amani, 2018) concentrated on heat transmission and pressure drop in a metal foam-coated five-row tube array. When compared to an uncoated tube array, the results demonstrated that applying a small layer of metal foam to the tubes greatly improved heat transfer.

CONCLUSIONS

This paper provides a comprehensive review of studies that deals with channels with and without porous materials. It focuses on how the flow efficiency and heat transfer stability of porous materials with nanoparticles are affected by the presence of porous media and thermal conditions:

1) The results demonstrate that by regulating the dispersion, aggregation, and flow properties of nanoparticles in the presence of porous media, nanofluids significantly improve heat transfer performance.
2) This paper emphasizes the importance of understanding the distribution of streamlines in channels involving porous media and nanofluids in the thermal system in general.
3) It investigates the effects of flow conditions, whether porous media is present or not, on the flow and heat transfer properties within the channels.
4) In addition, it is demonstrated that while the presence of porous media improves the overall heat transfer efficiency, it also causes a significant increase in the pressure drop across the layer.

RECOMMENDATIONS

Enhance models and sensor sensitivity, integrate AI for data analysis, expand industrial applications, develop portable systems, and test on complex multiphase flows to improve performance.

FURTHER WORK

the methodologies can be generalized for future work by refining models, improving sensing technologies, and adapting them to more complex systems and diverse industrial environments.

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