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ENHANCING FORCED CONVECTIVE HEAT TRANSFER IN A SINUSOIDAL DUCT BY INSERTION OF POROUS MATERIAL

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Abstract

The porous material helps to disrupt the flow and promote better heat transfer between the fluid and the duct walls. This method is commonly used in applications requiring efficient cooling or heating, such as heat exchangers or electronic cooling systems. Utilizing a porous medium with high heat conductivity and a corrugated channel will result in further improvement. The current study optimizes forced convective heat transfer through a sinusoidal wavy channel inside a porous media. Design engineering software is necessary to simulate the thermal improvement model utilizing forced heat transfer, and the model was created using the SolidWorks program with dimensions of a channel with a length of 1 m and a square cross-section with a side length of 0.15 m. The channel contains two bends with a wavelength of 0.5 m and a wave height of 0.05 m, and the position of the pore in the middle of the channel has a length of 0.2 m with a cross-section like the cross-section of the channel. After completing the model design process, it was started using the COMSOL Multiphysics program. The results showed that the temperature is clearly affected by an increase in the flow rate and a decrease in the porosity ratio, as it was found that the best temperature that could be reached is at a velocity of 0.1 m/s and a porosity ratio of 0.3 where the temperature was 314 K, which is the highest temperature that could be reached. The pressure at the entry area visibly increases as the flow velocity increases, and because porous material is present, the pressure lowers dramatically. For example, the pressure value at the velocity was 1 m/s 1400 pa, where this pressure was reduced to 0 pa.

Keywords: CFD, Channel, COMSOL Multiphysics, Duct, Porous media, Sinusoidal.

1. Introduction

Some applications and processes where curved channels with porous media were commonly employed are curved channels with a porous medium can be incorporated into heat exchangers to increase the heat transfer rate between the hot and cold fluids. Also, compact heat exchangers often utilize curved channels with a porous medium to achieve higher heat transfer rates in a smaller footprint. In electronic cooling systems, curved channels with a porous medium can be employed to dissipate heat generated by electronic components. Curved channels with a porous medium can be utilized in solar thermal systems to enhance heat absorption from sunlight. Curved channels with a porous medium can be employed in power generation systems like gas turbines or steam generators. Also, fuel cells utilize curved channels with a porous medium to enhance heat transfer between the reactant gases and the electrode surfaces.

The fundamental upgrade parameter in the method for combining asymptotes is the dimensionless warm length (x). When the structure is advanced with a fixed hotness move thickness, the highest possible benefits of both x and D/L are close to those that contrast with joint strain drop and siphoning power reduction [1]. The heated movement applied to channel dividers is transferred into fluid thanks to the homogenous spacing and high conductivity of porous media. The temperature differential between the channel dividers and the mean fluid temperature are inversely correlated with the heat transfer coefficient. The temperature differential between the channel dividers and the fluid's mean temperature increases, increasing the heat transfer coefficient. The best warm execution in a turbulent stream is demonstrated by a channel with annulus-shaped porous zones (the penetrable zone put close to the divider), which may convey a significant amount of heat with little strain decrease [2]. Pourrahmani et al. [3] mathematically assessed the convective hotness move upgrade of the proton trade layer power modules (PEMFC). Because larger hotness moving surfaces cause increased hotness rates, a level plate permeable layer is used in the gas stream channel. Results show that Nu grows by increasing the size of MPL and GDL overall, despite these sizes only slightly altering the hotness move.

Due to the addition of the porous material, heat transfer has improved, and there has also been a very large strain drop. Results show that the general hotness sink performance is enhanced at low stream rates, porosities, and high nanoparticle centralizations [4]. Three different low, transitional, and high biofilm levels, corresponding to 2.7%, 17.6%, and 55.2%, were created in a microfluidic channel using E. coli biofilms and a Sinclair layer of glass dabs. By digitizing confocal images and accounting for a wide variety of biofilm penetrability, two-layered biofilm patterns and appropriations in the porous media were exhibited (kb) [5].

Understanding the fundamentals of the liquid stream necessitates the first fluidized approach of yield-stress liquids in difficult permeable mediums. It can be demonstrated that the tension drop required to open the major channel for a specific yield pressure depends on both the relative plate size and the framework's observable length L. Also, the pressing division for porous media is built of non-covering circles [6]. The hotness movement and entropy age inside a channel partially filled with an N-layer permeable medium are investigated in this work. The Nusselt number, the absolute entropy aging rate, the Bejan number, and the grating component are all computed using the scientific answers for the speed and temperature in the channel.

The pressure progression limit condition and the hotness transition coherence limit conditions depict the force and hotness movement at the connection point between two separate permeable layers [7]. According to a review, the penetrability variation caused by hydrate separation will impact the subsequent misuse of hydrate during the development of gaseous petrol hydrate.

Another model has been developed by Hou et al. 8] to determine the penetrability of gas hydrates in porous mediums. It demonstrates that under exploratory conditions, hydrate fills fundamentally in the pore focus and is sensitive to the hydration-arrangement propensity and shape in the pore site. The non-Newtonian power-regulation liquid stream's two-layered limited convection heat transfer between two equal plates loaded up with, to some extent, permeable media is concentrated numerically. The numerical model utilized the warm grid Boltzmann strategy. Shear-diminishing (n=0.8), Newtonian, and other liquids are utilized to explore the conduct of force Law liquids. Reynolds numbers have an effect of between 100 and 999 and are displayed to have no critical impact on heat movement in this analysis [9]. The movement of heat and liquid in a tube made up of multifaceted metal froth is almost flawless. The energy and energy situations in the porous location are settled using Darcy-Brinkman-Horkheimer and neighbourhood warm non-balance procedures. At increasing porosities and molecule widths of the metal foam, the validity of the local thermal balancing approach is unclear [10].

Nazari and Toghraie [11] considered constant heat flux and thermal equilibrium, convective heat transfer in a sinusoidal channel with porous media. Results show increased Nusselt number and convection heat transfer coefficient, temperature gradient rises with Reynolds number and decreased temperature differential in porous areas. Baragh et al. [12] investigated heat transport in porous zones in a circle-shaped channel, focusing on hydrodynamic parameters, porous media improvement, and pressure drops. Results show that filled porous media channels enhance heat transfer, while annulus-shaped porous zones have the best thermal performance in turbulent flows. Bibin and Jayakumar [13] analysed pressure drop and forced convective heat transfer in square ducts filled with porous material. It considers porosity, thickness ratio, and heat transport using Open FOAM. Results show that porous inserts improve heat transfer and minimize pressure drop. The porous medium's thickness ratio affects heat transmission and pressure reduction. Aminian et al. [14] discussed the impact of geometrical parameters on heat transfer and entropy production optimization in porous mediums. The Darcy-Brinkman-Forchheimer model was applied, showing increased thermal entropy creation, and decreased frictional entropy generation. The ideal geometry for nanoparticles was chosen. Numerical analysis examines the impact of porous inserts on forced convection in circular conduits [15]. Two configurations are studied: annular porous material and core filled with porous substance. The Darcy-Brinkman-Forchheimer model simulates flow within the porous material. The ideal thickness is 0.6, with a tolerable pressure drop.

Yang et al. [16] analysed forced convective heat transfer in porous pin fin channels using the Forchheimer-Brinkman extended Darcy and two-equation energy models. Results show that porous pin fins improve heat transfer and reduce pressure drops with optimal physical parameter selection. Long elliptic channels have higher overall heat transfer efficiency.

Open-cell metal foam, with its porous structure and large contact surface area, offers the potential for high heat flux thermal management applications. Its low density and open-celled structure make it ideal for forced convection in heated channels [17]. Local Nusselt values were found on parallel plate channels' porosity and fluid sides. Wall heat transfer improvements are most effective at 0.8 porous fractions and 0.001 Darcy number. The highest enhancement per unit pressure decrease occurs at 0.7 porous fractions [18]. A numerical study investigates heat transfer and flow in a sinusoidal parallel-plate heat exchanger using metal foam in diverging regions [19]. Results show that using metal foam increases heat transfer rate, effectiveness, and overall heat transfer coefficient by 19.2%. Azzawi et al. [20] studied the heat transfer enhancement gained by various channel geometries using nanofluids and porous medium using CFD numerical analysis. They reported that heat flux and heat transfer rate increased as the porosity decreased.

Most of the previous research focused either on the percentage of porosity or on the curved channel. Also, no previous research could use these two methods to help improve temperature transfer by forced convection. This was collected during this research paper to obtain accurate results. The originality of this paper is in how to use the sine wave dictate and the presence of porous material in the transmission of thermal energy.

2. Methodology

2.1. Domain design

The simulation of the thermal improvement model by forced heat transfer requires a design engineering program, where the model was designed using the SolidWorks program with dimensions of a square cross-section with a side length of 0.15 m and a channel with a length of 1.0 m, where channel contains two bends as a wavelength of 0.5 m and a wave height of 0.05 m and with the position of the pore in the middle of the channel with a length of 0.2 m for a cross-section similar to the cross-section of the channel, as in the following Fig. 1.

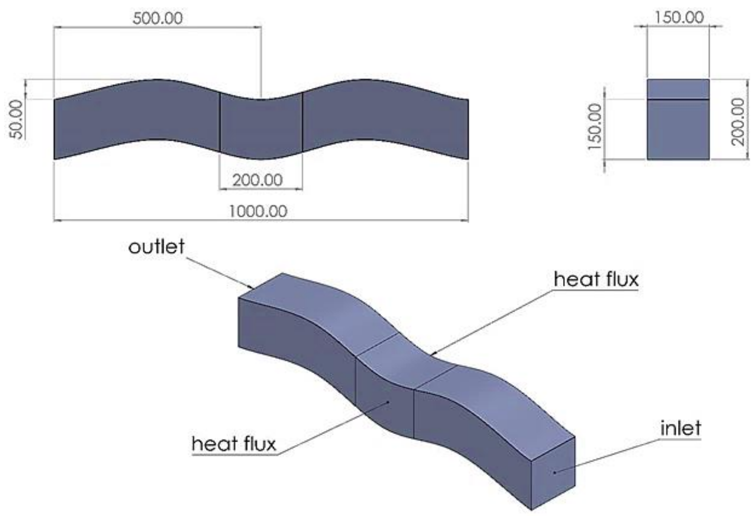


Fig. 1. Geometry and dimensions of the computational model.

2.2. Mesh generation and independency check

The COMSOL Multiphysics application simulation is launched after the complete model design phase. To generate precise findings that can be compared with real-world applications, an adequate mesh must be created, Fig. 2, with mesh dependability increasing until a stable result is attained. The temperature in this work is stable and had a value of 313.85 K. A tetrahedron mesh was utilized with several elements that reached 185,294 in total, as shown in Table 1. The element size was 0.01 m, and the type was tetrahedron.

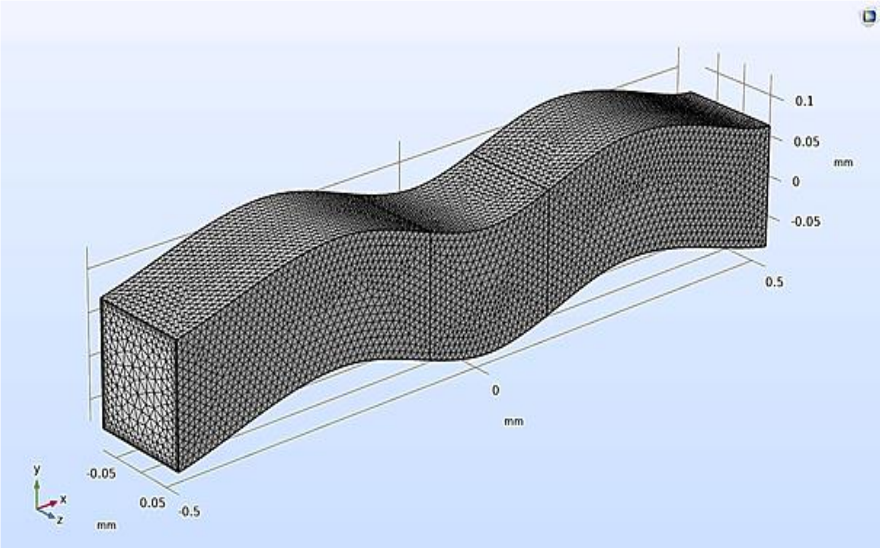


Fig. 2. Geometry mesh.

Table 1. Mesh independence.

Case	Element	Max temperature (K)	Percentage of change in max temperature
1	61343	317.34	--
2	103745	314.63	0.854
3	144766	313.86	0.247
4	185294	313.85	0.003

2.3. Assumptions

In the current study, water is considered as the running liquid, and the characteristics of flow are assumed to be steady flow, three dimensional, Newtonian, incompressible, and turbulent.

Computational Fluid Dynamics (CFD) is a COMSOL processor that simulates certain systems' fluids and thermals. Studies are performed to grow a more profound knowledge of the stream field. To explain the impact of the choppiness model, which includes the arrangement of two transport equations, the k-ε model is utilized. Thus, the strategies of the mathematical arrangement will tackle these Cartesian direction frameworks (x, y, and z). Three-dimensional simulation is produced.

2.4. Boundary condition

A different Reynolds number was used in the entry area (3182, 9548, 15913, 25460, 31825). The boundary conditions are shown in Table 2. The entry temperature was 300 K, where water was used in this simulation, and different porosity ratios ranging from 0.3 to 0.9 with a difference of 0.3 were used to make a clear comparison Between the extracted results and see a clear improvement in heat transfer by forced convection, where a fixed heat source of 1000 W/m2 was added, where the study was variable with time by 1.5 s and with a time step of 0.005 s to clearly see the changes in the process of flow and heat transfer.

Table 2. Boundary conditions.

Part	Type	Boundary condition	
		Momentum Conditions	Thermal Condition
Inlet	Velocity inlet	0.1, 0.3, 0.5, 0.8, 1 m/s	300 K
Outlet	Pressure outlet	0 Pa	300 K
Porous wall	Wall	Stationary	Heat flux=1000 W/m^2

2.5. Governing equations

The governing equations for fluid flow in 3D simulations using COMSOL are the Navier-Stokes equations, which describe the conservation of momentum and the continuity equation for incompressible flows. These equations are commonly used for modelling fluid flows in various engineering and scientific applications. The Navier-Stokes equations in 3D for an incompressible fluid are as follows:

The Navier-Stokes equations describe the conservation of momentum and are given by:

- Continuity equation:

$$\nabla \cdot (\rho\, v) = 0 \tag{1}$$

- Momentum equation:

$$\rho(v \cdot \nabla)v = -\nabla P + \rho g + \nabla \tau \tag{2}$$

where ρ is the fluid density, u is the velocity vector, t is time, p is the pressure, μ is the dynamic viscosity, g is the gravitational acceleration vector.

- Energy Equation:

The energy equation governs the transport of thermal energy in the fluid and is given by:

$$\nabla \cdot (\rho\, Cp\, T\, v) = \nabla \cdot \left(k_{eff}\ \nabla T\right) + Q \tag{3}$$

where Cp is the specific heat at constant pressure, T is the temperature of the fluid, k_{eff} is the effective thermal conductivity, Q is the volumetric heat source.

Darcy's Law is a fundamental equation used to describe fluid flow through porous media. It relates the fluid velocity to the pressure gradient and permeability of the porous medium. In COMSOL, Darcy's Law can be expressed as:

$$\nabla \cdot (-k\ \nabla D) = f \tag{4}$$

where, ∇ is the gradient operator, k is the permeability of the porous medium, P is the fluid pressure, and f represents any external forcing or source terms.

The porosity ratio, often denoted as ε, is a dimensionless parameter used to describe the void fraction or the ratio of the volume of voids (pores) to the total volume of a porous medium. It is commonly used in the context of porous media modelling and affects various physical processes, such as fluid flow and heat transfer.

In COMSOL, the porosity ratio can be incorporated into the governing equations through the permeability term, which quantifies the ability of fluid to flow through the porous medium. The relationship between the porosity ratio and permeability depends on the specific porous media model and can be defined using empirical correlations or experimental data. Fluid flow instability can lead to unpredictable and chaotic behaviour, affecting the heat transfer performance and overall system behaviour. One common instability that can arise is the onset of flow oscillations or pressure fluctuations. Various factors, such as flow velocity, porosity, permeability, and the geometry of the porous material, may trigger these instabilities.

3. Results and Discussion

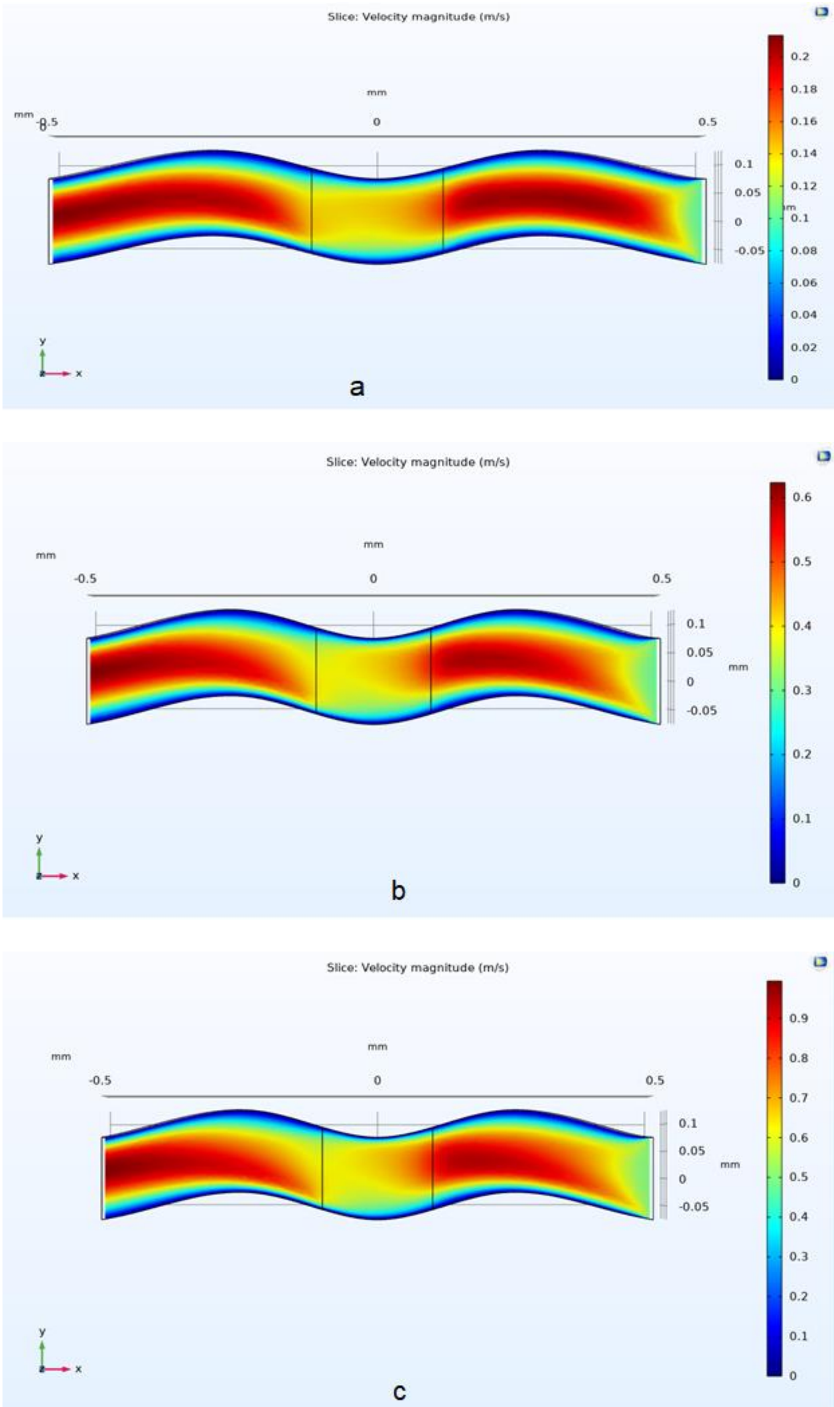
3.1. Effect of fluid flow velocity on forced convection heat transfer

A variable flow Reynolds number was used in the entry area (3182, 9548, 15913, 25460, 31825) to see the clear gradient in the heat energy value transferred by forced convection, as shown in Fig. 3. The flow velocity greatly affects the amount of heat transfer. The results showed an increase in the flow velocity. The fluid decreases the heat transfer value by forced convection.

The figures show that the velocity values are variable at the entry stream and affect water flow inside the porous cavities. A material's permeability and porosity affect fluid flow in a porous medium. The characteristics of the porous material and the flow conditions can affect how fluid moves through it, changing the velocity distribution. The flow behaviour inside the porous cavities changes due to variations in the velocity at the entering stream. Higher stream entrance velocities might cause more turbulence and pressure drop inside the porous medium. By increasing mixing and convective heat transfer between the fluid and the porous material, this turbulence and pressure drop also help.

On the other hand, slower speeds might lead to laminar flow patterns and a smaller pressure drop through the porous medium. This can restrict convective heat transmission, although it might still be adequate for some applications, especially if lowering pressure losses is the main goal. Examining the velocity contours makes it possible to determine the precise impacts of different velocity values on the flow behaviour within the porous material.

Visual representations of the distribution of velocities within a flow field are called velocity contours. Examining the contours, one may see how the fluid velocity varies and interacts with the porous media. Variations in the entrance stream's velocity can greatly impact how the flow behaves inside porous cavities. While lower velocities or Reynolds numbers provide more laminar flow patterns with less pressure loss, higher velocities or Reynolds numbers encourage turbulence and convective heat transfer. Velocity contours give these variations a visual representation, which helps decipher and study the flow dynamics in porous media.


Slice: Velocity magnitude (m/s)
a
Slice: Velocity magnitude (m/s)
b
Slice: Velocity magnitude (m/s)
c

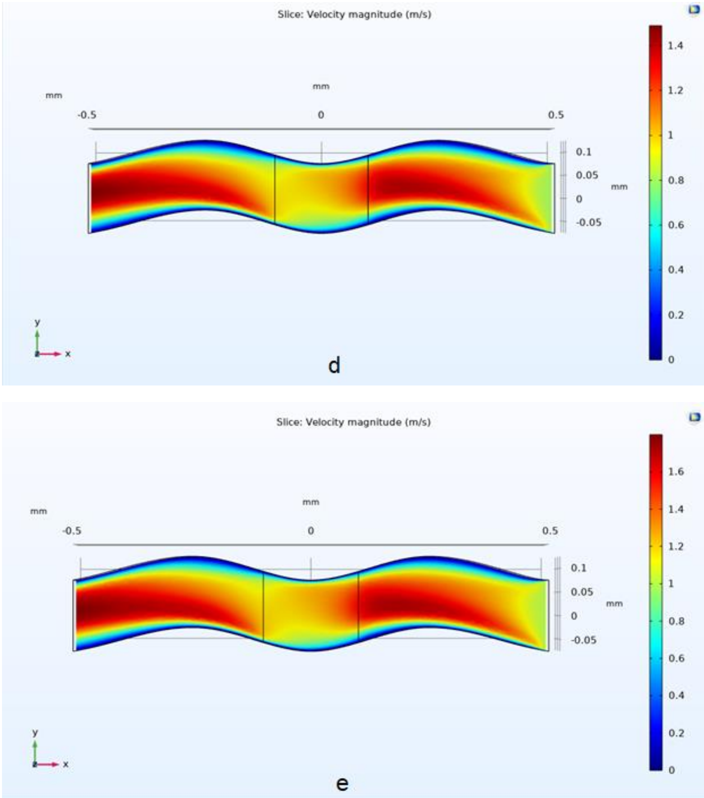
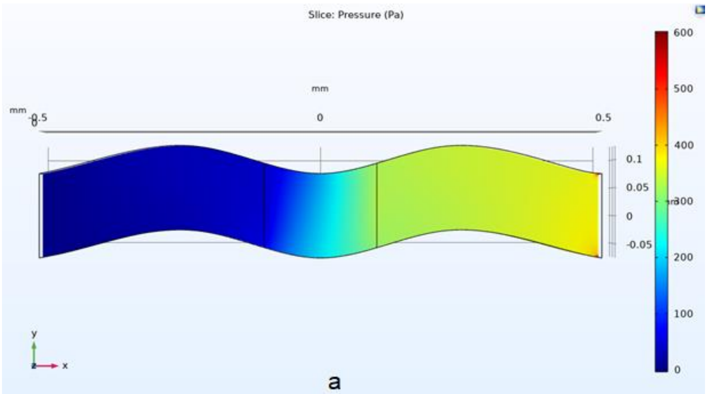


**Fig. 3. Velocity contour. (a) 0.1 m/s,
(b) 0.3 m/s, (c) 0.5 m/s, (d) 0.8 m/s, (e) 1 m/s.**

Through the results of the pressures, as shown in Fig. 4, we note that the value of the pressures increases with the increased fluid flow rate, resulting in a reduction in the amount of heat transfer by forced convection, as it was found that at speed 1 m/s, the value of the pressure is 1400 pa, as this pressure is to a large extent capable of allowing the fluid to pass with a high flow through the porous cavities. Thus, the value of the heat transferred to the fluid from the walls of the porous material decreases due to forced convection heat transfer.



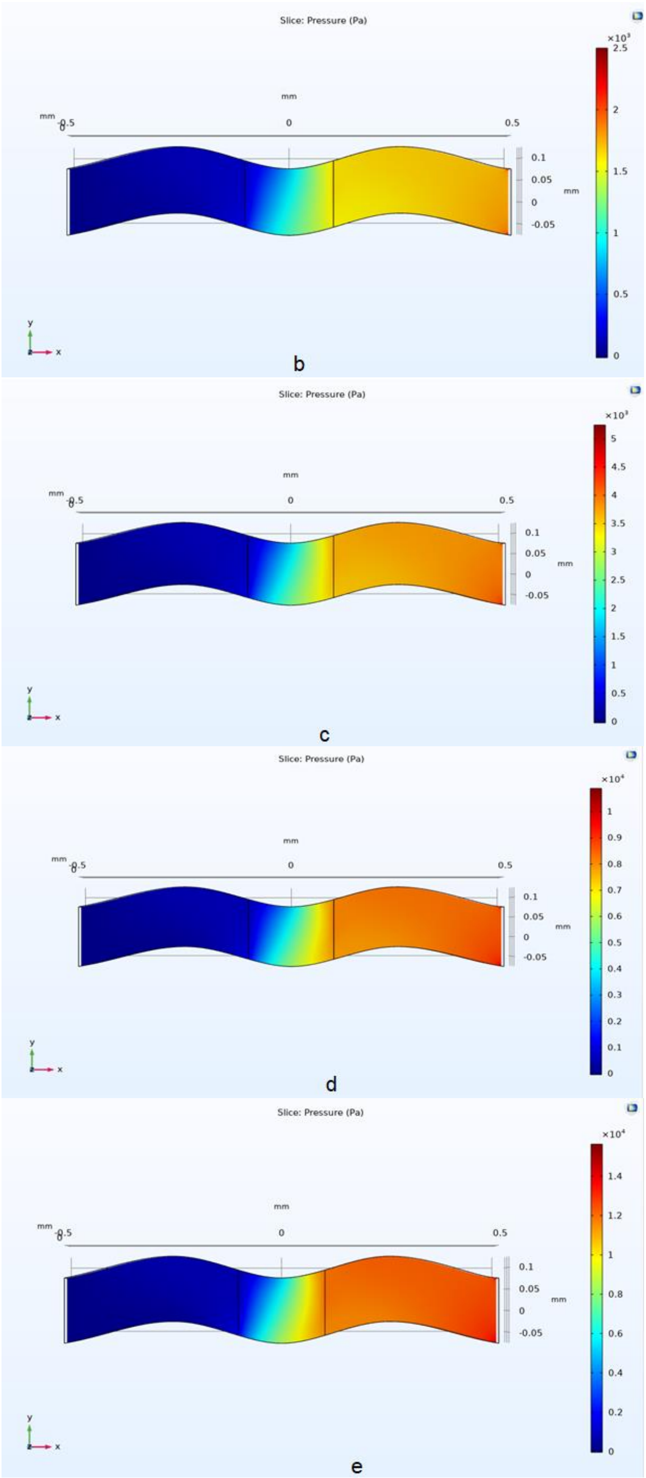
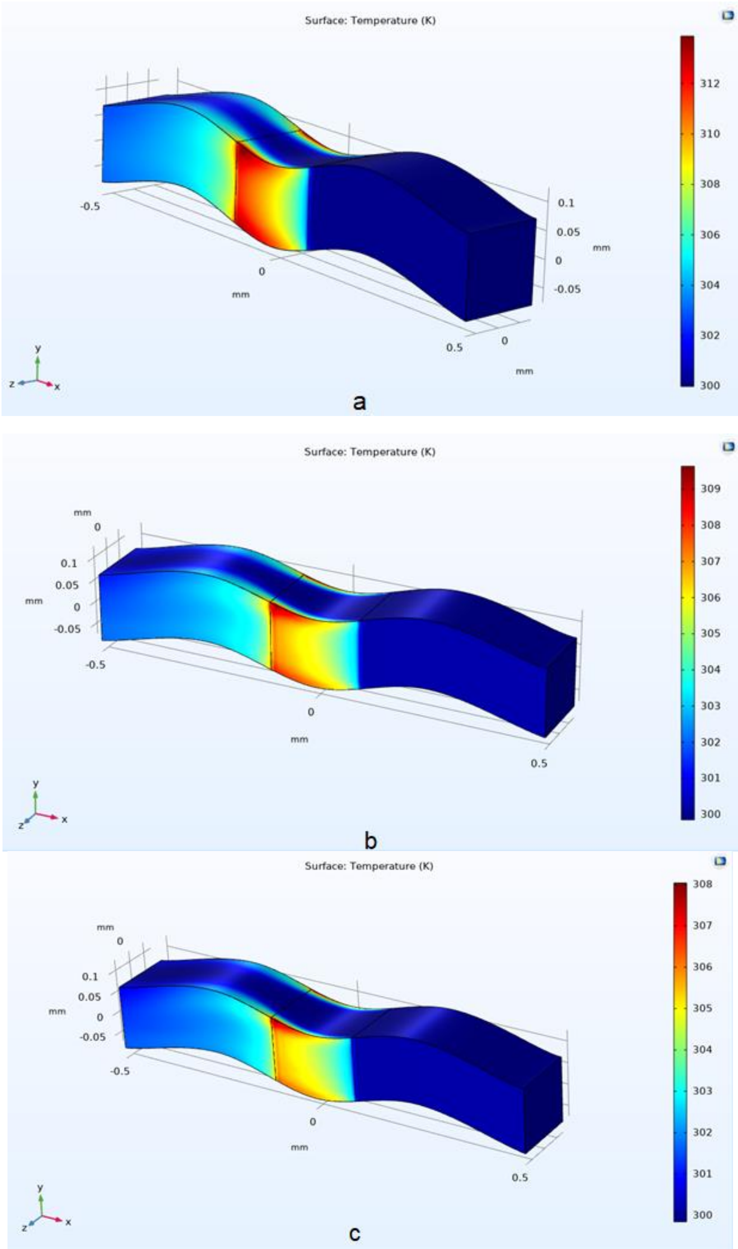


**Fig. 4. Velocity contour. (a) 0.1 m/s,
(b) 0.3 m/s, (c) 0.5 m/s, (d) 0.8 m/s, (e) 1 m/s.**

Since the fluid flow velocity was 1 m/s and the temperature was 306 K, the forced convection method of transferring heat was significantly impacted, and this decrease in temperatures is due to the fluid flow velocity that does not allow enough time for the water to transfer heat to it either at the speed 0.1 m/s. The temperature reached 314 K, as shown in Fig. 5, which is considered the highest temperature the fluid reached at the exit area, and the reason for this is to give the necessary time for the fluid to transfer heat to it.



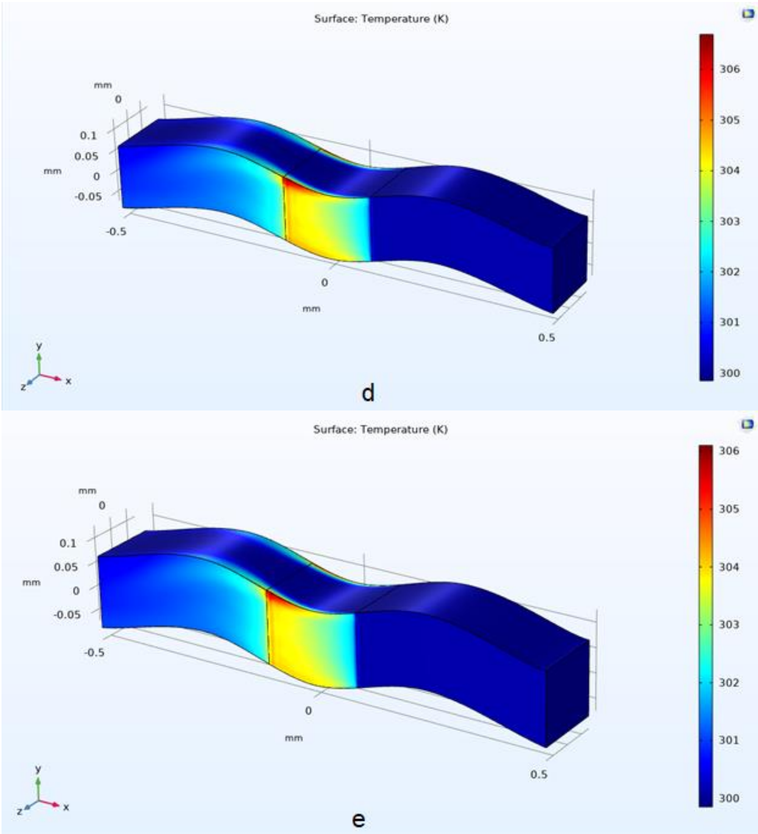


**Fig. 5. Temperature contour. (a) 0.1 m/s,
(b) 0.3 m/s, (c) 0.5 m/s, (d) 0.8 m/s, (e) 1 m/s.**

3.2. **Effect of porosity**

The effect of the porosity ratio of the material works greatly on the decrease in pressure during the fluid flow and a decrease in its velocity, as this decrease gives enough time for the fluid to receive a larger amount of heat. Naturally, the lower porosity ratio increases the obstruction to the fluid flow and thus increases the heat transfer by forced convection. The porosity ratios were used since the best velocity in the previous figures is 0.1 m/s.

Results in Fig. 6 shows that the temperature fluctuates with the decrease in the porosity ratio, as at a porosity ratio of 0.3, the highest temperature reached by the fluid is 314 K due to obstruction of the fluid's flow velocity and giving it more time to receive heat transfer by forced convection, while the porosity ratio reached 0.9 degrees at temperature of 312.4 K, which is lower compared to other percentages.

Figure 7 shows the correlation between the water outlet temperature and the charging flow rate as inlet velocity. It shows that when the velocity increases, the water outlet temperature decreases. At 0.3 m/s inlet flow, the temperature is 312 K, while by increasing the charging to a velocity of 1.0 m/s, the outlet temperature drops to 305 K.

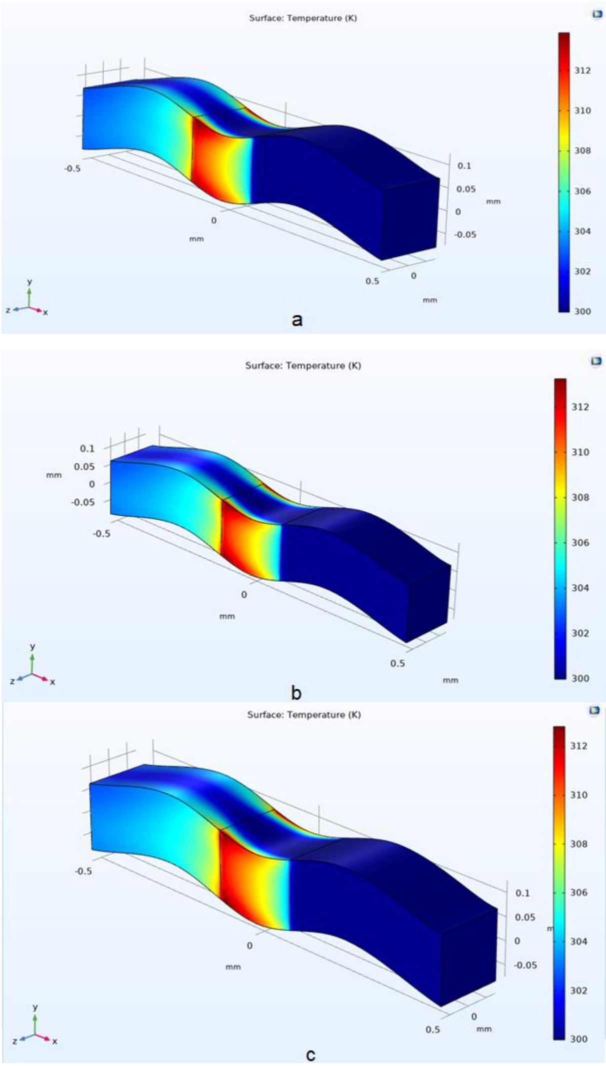


Fig. 6. Temperature contour. (a) 0.3 m/s, (b) 0.6 m/s, (c) 0.9 m/s.

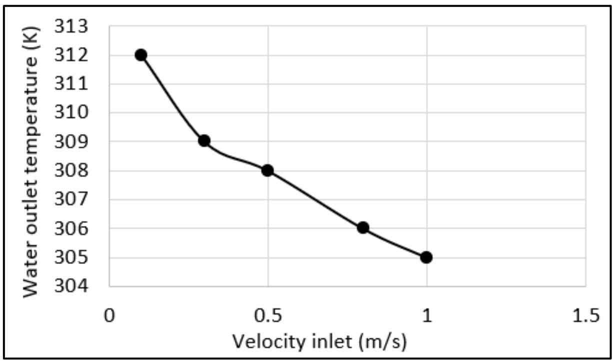


Fig. 7. Change of outlet water temperature at various water velocities.

Figure 8 shows the maximum temperature gradient with porosity. When the porosity increases from 0.3 to 0.9, the outlet water temperature decreases from 316 K to 309 K. Such results declare the high effectiveness of porosity on the hydrothermal process.

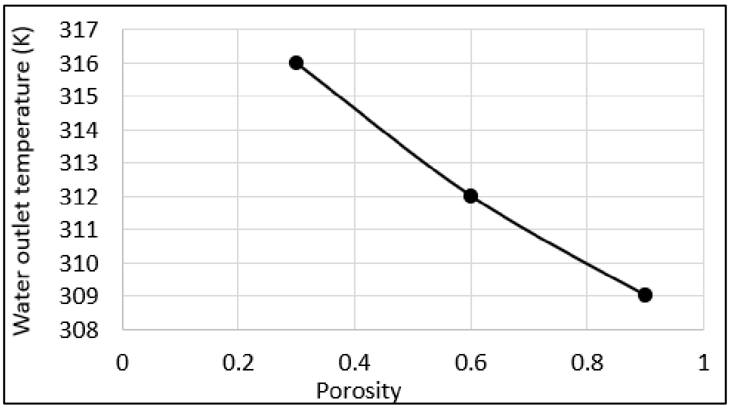


Fig. 8. Change of outlet water temperature at various porosities.

4. Conclusions

A wavy channel with a porous material that improves heat transfer by forced convection has been investigated by numerical simulation. Results revealed that the temperature is obviously affected by an increase in the flow rate and a decrease in the porosity ratio, which is the highest temperature that could be reached. The increase in the fluid flow velocity works on a gliding velocity within the porous material stream and does not give enough time for heat transfer by forced convection. The best velocity was 0.1 m/s, with the highest temperature reaching 314 K using 0.3 porosity. Increasing the flow velocity increases the pressure at the entry area, and due to the presence of the porous material, the pressure decreases significantly, as the pressure value at the velocity was 1 m/s 1400 Pa, where this pressure decreased to 0 Pa. Increasing the duct angle caused fluid disturbance.

Acknowledgements

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Nomenclatures

Cp	The specific heat capacity
f	Forcing function
g	The acceleration due to gravity, m/s^2
k	Constant coefficient
P	Pressure, Pa
Q	Heat source or heat sink within the fluid, W
T	Temperature, K

Greek Symbols

∇	Represents the divergence
∇v	The gradient of the velocity vector
$-\nabla p$	This term represents the pressure gradient within the fluid. It accounts for the pressure variation in the fluid, which drives the fluid flow from regions of higher pressure to lower pressure
v	The velocity vector of the fluid
μ	Dynamic viscosity
ρ	The density of the fluid

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