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Thermo-Hydraulic Analysis of Non-Newtonian Nanofluid Flow in Porous Wavy Microchannels

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Abstract

In the present study, the thermo-hydraulic performance of non-Newtonian nanofluid flow inside a porous wavy microchannel was numerically investigated under different permeability conditions. The computational model was developed based on a two-dimensional steady-state laminar flow formulation using the Darcy-Brinkman approach to simulate the transport phenomena inside the porous medium. The effects of permeability on velocity distribution, temperature field, heat transfer enhancement, pressure drop, and friction characteristics were comprehensively analyzed. The numerical results demonstrated that permeability has a significant influence on both the thermal and hydrodynamic behavior of the nanofluid flow inside the porous microchannel. Increasing permeability reduced the porous resistance force and enhanced fluid circulation throughout the channel, resulting in improved convective heat transfer performance. The obtained results indicated that the average Nusselt number increased with increasing permeability due to stronger thermal mixing and thermal boundary layer disruption generated by the wavy geometry. Furthermore, the sinusoidal microchannel configuration intensified local flow disturbances and secondary vortical structures, which contributed to additional heat transfer enhancement. However, lower permeability conditions produced larger pressure drops and higher friction factors because of stronger hydrodynamic resistance effects inside the porous region. The present numerical investigation confirmed that the combined utilization of porous media, wavy microchannel geometry, and non-Newtonian nanofluids can significantly improve the thermo-hydraulic performance of compact thermal systems. The obtained findings provide useful insight for the design and optimization of advanced cooling technologies employed in microelectronic devices, compact heat exchangers, and MEMS-based thermal management systems.

Keywords: Non-Newtonian nanofluid, Porous medium, Wavy microchannel, Permeability, Pressure drop, Friction factor.

1 | Introduction

The rapid development of compact thermal systems and micro-scale devices has significantly increased the demand for efficient heat transfer technologies in recent years. Microchannels have attracted considerable

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attention due to their high surface-to-volume ratio, compact structure, and remarkable capability for thermal management in applications such as microelectronic cooling systems, biomedical devices, heat exchangers, MEMS technologies, and energy conversion systems [1–4]. However, despite their favorable thermal characteristics, conventional microchannels often suffer from substantial pressure drops and limited thermal efficiency under high heat flux conditions [5]. Therefore, improving the thermo-hydraulic performance of microchannel systems has become one of the major challenges in modern thermal engineering [6]. One of the most effective approaches for enhancing heat transfer in microchannels is the utilization of nanofluids. Nanofluids are engineered fluids containing suspended nanoparticles with high thermal conductivity inside a base fluid. The addition of nanoparticles considerably improves thermal transport properties and increases the overall heat transfer coefficient compared with conventional working fluids [7–10]. Numerous experimental and numerical investigations have demonstrated that nanofluids can significantly enhance convective heat transfer performance while maintaining acceptable flow characteristics. Among various categories of nanofluids, non-Newtonian nanofluids have gained increasing attention because many industrial and biological fluids exhibit non-Newtonian behavior. In such fluids, the viscosity is dependent on the shear rate, leading to more complex flow characteristics compared with Newtonian fluids. The application of non-Newtonian nanofluids in micro-scale thermal systems has shown promising potential in improving cooling efficiency [11–14]. Nevertheless, the complex rheological behavior of these fluids strongly affects velocity distribution, wall shear stress, thermal boundary layer development, and pressure drop characteristics. Consequently, detailed investigations are required to better understand the coupled thermal and hydrodynamic behavior of non-Newtonian nanofluid flows inside microchannels. In addition to the selection of advanced working fluids, geometrical modification of microchannels is another important technique for thermal enhancement [10]. Wavy microchannels have been extensively studied because the corrugated geometry generates secondary flow structures, fluid mixing, and flow disturbance, which intensify thermal transport mechanisms. Compared with straight microchannels, wavy configurations can improve heat transfer rates by disrupting the thermal boundary layer and increasing fluid mixing near heated walls. However, the enhancement in heat transfer is usually accompanied by an increase in friction losses and pressure drop. Therefore, achieving an optimal balance between thermal enhancement and hydrodynamic performance remains an important research objective [9–13]. Another effective strategy for improving thermo-hydraulic performance is the incorporation of porous media inside the microchannel domain. Porous structures increase the effective heat transfer surface area and promote thermal dispersion within the fluid region. The presence of porous media can significantly alter velocity profiles, flow resistance, and thermal fields [7]. In porous channels, permeability is one of the most influential parameters governing fluid motion and transport behavior. A decrease in permeability generally increases flow resistance and pressure losses, whereas higher permeability facilitates fluid movement through the porous matrix. Therefore, permeability plays a critical role in determining the overall thermal and hydrodynamic efficiency of porous microchannel systems. Several studies have investigated the influence of porous media on convective heat transfer enhancement in microchannels. Previous research has shown that porous structures can improve heat transfer performance due to increased mixing and enlarged heat transfer area [4]. However, excessive resistance induced by low-permeability porous materials may adversely affect the pumping power requirements. Consequently, optimization of porous medium permeability is essential for practical engineering applications. Furthermore, the simultaneous effects of porous media, non-Newtonian nanofluids, and wavy geometries create highly coupled transport phenomena that are not yet fully understood. Although numerous studies have separately examined nanofluid flows, porous microchannels, or wavy channel configurations, comprehensive investigations addressing the combined influence of these parameters remain limited in the literature. In particular, the effect of porous medium permeability on the thermo-hydraulic behavior of non-Newtonian nanofluids flowing through wavy microchannels requires further investigation [15–19]. The thermo-hydraulic performance of such systems is commonly evaluated using parameters such as the Nusselt number, friction factor, pressure drop, and flow resistance characteristics. Understanding the interaction between permeability and these performance indicators is essential for designing efficient thermal systems with improved heat transfer capability and minimized energy consumption. Accordingly, the present study numerically investigates the thermo-hydraulic performance of non-Newtonian nanofluid flow inside a porous wavy microchannel. Special attention is devoted to examining the effects of porous medium permeability on heat transfer enhancement and friction characteristics. The governing equations for continuity, momentum, and energy are solved under appropriate boundary conditions, and the influence of permeability variations on velocity distribution, temperature fields, Nusselt number, and pressure drop is comprehensively analyzed [4–9]. The obtained results provide useful insights into the design and optimization of advanced micro-scale thermal systems employing porous structures and non-Newtonian nanofluids. The novelty of the present work lies in the simultaneous consideration of non-Newtonian nanofluid behavior, porous medium permeability, and wavy microchannel geometry in a unified thermo-hydraulic framework. Unlike many previous studies that focused on either straight channels or Newtonian fluids, the current investigation aims to provide a more realistic and comprehensive analysis of transport phenomena in advanced microchannel systems [8–10]. The findings of this study can contribute to the development of high-performance cooling devices and enhanced thermal management technologies for modern engineering applications. To the best of the authors' knowledge, limited studies have simultaneously investigated the combined effects of porous medium permeability, sinusoidal wavy geometry, and non-Newtonian nanofluid behavior on thermo-hydraulic transport phenomena inside microchannels. Therefore, the present study aims to provide a comprehensive numerical analysis of heat transfer enhancement and hydrodynamic characteristics under different permeability conditions.

2 | Physical Model and Problem Description

A two-dimensional porous wavy microchannel is considered in the present study to investigate the thermo-hydraulic behavior of non-Newtonian nanofluid flow under different permeability conditions. The computational domain consists of a sinusoidal microchannel filled with a homogeneous porous medium [15]. The wavy geometry is selected due to its superior capability in enhancing fluid mixing and improving convective heat transfer compared with conventional straight microchannels. The upper and lower walls of the microchannel are modeled using periodic sinusoidal functions in order to generate a corrugated flow passage [16–18]. The fluid enters the microchannel with a uniform inlet velocity and constant inlet temperature, while a pressure outlet boundary condition is imposed at the channel exit. The channel walls are subjected to a constant temperature condition to simulate thermal loading during the heat transfer process.

The porous region inside the microchannel is assumed to be homogeneous and isotropic. The flow through the porous medium is modeled using the Darcy-Brinkman approach, which accounts for both permeability resistance and viscous diffusion effects. The permeability of the porous matrix is considered one of the primary controlling parameters in the present investigation. Variations in permeability significantly influence the flow resistance, thermal boundary layer development, and pressure drop characteristics inside the microchannel. The working fluid is considered to be an incompressible non-Newtonian nanofluid with laminar flow behavior. The thermophysical properties of the nanofluid are assumed to remain constant throughout the computational domain. The non-Newtonian behavior of the fluid is modeled using an appropriate rheological model to capture the shear-dependent viscosity characteristics of the nanofluid. To simplify the mathematical formulation, several assumptions are adopted in the present study. The flow is assumed to be steady, two-dimensional, and laminar. Thermal radiation, body force effects, and viscous dissipation are neglected. Furthermore, the porous matrix and the nanofluid are assumed to be in local thermal equilibrium. These assumptions are widely accepted in the numerical analysis of micro-scale thermal systems and provide reliable predictions for thermo-hydrodynamic transport phenomena [6]. The geometrical parameters include the channel length L, hydraulic diameter Dh, wave amplitude A, and wavelength λ. The sinusoidal wall profile is mathematically expressed in *Eq. (1)* as:

$$y = A\sin\left(\frac{2\pi x}{\lambda}\right), \tag{1}$$

where A represents the wave amplitude, and λ denotes the wavelength of the corrugated wall. The thermo-hydraulic performance of the system is evaluated using important engineering parameters such as the Nusselt number, friction factor, and pressure drop. The average Nusselt number is employed to characterize the convective heat transfer enhancement, while the friction factor is used to evaluate the hydrodynamic losses induced by the porous structure and wavy geometry [9]. The present numerical model aims to investigate the coupled effects of porous medium permeability and wavy channel geometry on the transport characteristics of non-Newtonian nanofluids. The obtained results provide valuable insight into the optimization of advanced microchannel cooling systems with enhanced thermal performance and reduced hydraulic resistance.

3 | Governing Equations

The thermo-hydrodynamic behavior of non-Newtonian nanofluid flow inside the porous wavy microchannel is governed by the conservation equations of mass, momentum, and energy. The governing equations are formulated based on the assumptions of steady-state, two-dimensional, incompressible, and laminar flow conditions. The porous medium effects are incorporated through the Darcy-Brinkman model in order to account for both permeability resistance and viscous diffusion within the porous region [19]. In addition, the rheological behavior of the non-Newtonian nanofluid is modeled using the power-law model to capture the shear-dependent viscosity characteristics of the working fluid.

3.1 | Continuity Equation

The conservation of mass for incompressible flow is represented by the continuity equation, which is written in *Eq. (2)* as:

$$\partial u/\partial x + \partial v/\partial y = 0, \tag{2}$$

where u and v denote the velocity components in the x and y directions, respectively. *Eq. (2)* ensures the conservation of mass throughout the computational domain and indicates that the net mass flux remains constant inside the porous wavy microchannel [8].

3.2 | Momentum Equations

The momentum transport inside the porous microchannel is governed by the Navier–Stokes equations modified by the Darcy-Brinkman formulation. The momentum equations account for the combined effects of pressure forces, viscous diffusion, inertial terms, and porous medium resistance. The x-direction momentum equation is expressed in *Eq. (3)* as:

$$\rho\,(u\,\partial u/\partial x + v\,\partial u/\partial y) = -\partial p/\partial x + \mu eff\,(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2) - (\mu/K)u. \tag{3}$$

Similarly, the momentum equation in the y-direction is given in *Eq. (4)* as:

$$\rho\,(u\,\partial v/\partial x + v\,\partial v/\partial y) = -\partial p/\partial y + \mu eff\,(\partial^2 v/\partial x^2 + \partial^2 v/\partial y^2) - (\mu/K)v, \tag{4}$$

where ϱ represents the fluid density, p is the pressure, μeff denotes the effective dynamic viscosity, and K indicates the permeability of the porous medium. The Darcy resistance term, represented by (μ/K), describes the momentum loss caused by the porous matrix. As the permeability decreases, the resistance force inside the porous medium increases, leading to higher pressure drops and stronger flow retardation effects within the microchannel. The Brinkman viscous diffusion term is included in *Eqs. (3)* and *(4)* to accurately capture the velocity distribution and shear effects near the channel walls [6], [7].

3.3 | Energy Equation

The heat transfer behavior of the non-Newtonian nanofluid inside the porous wavy microchannel is governed by the energy conservation equation. Under local thermal equilibrium conditions between the fluid and porous matrix, a single energy equation is employed throughout the computational domain. The energy equation is expressed in *Eq. (5)* as:

$$\rho cp\,(u\ \partial T/\partial x + v\ \partial T/\partial y) = keff\,(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2), \tag{5}$$

where T denotes the temperature, cp is the specific heat capacity of the nanofluid, and keff represents the effective thermal conductivity. The left-hand side of *Eq. (5)* represents convective heat transport due to fluid motion, while the right-hand side accounts for thermal diffusion inside the porous microchannel. The thermal conductivity enhancement caused by nanoparticle dispersion plays an important role in improving the heat transfer characteristics of the system [20].

3.4 | Non-Newtonian Nanofluid Model

The rheological behavior of the non-Newtonian nanofluid is modeled using the power-law model, which is commonly employed for shear-dependent fluids. According to this model, the effective viscosity varies as a function of the local shear rate.

The apparent viscosity is defined in *Eq. (6)* as:

$$\mu eff = m(\dot{\gamma})^{n-1}, \tag{6}$$

where m is the consistency index, n is the flow behavior index, and $\dot{\gamma}$ represents the shear rate. For values of n smaller than unity, the fluid exhibits shear-thinning behavior, whereas n greater than unity corresponds to shear-thickening behavior. When n equals unity, the fluid behaves as a Newtonian fluid with constant viscosity [21]. The power-law model provides an appropriate representation of the rheological characteristics of many industrial nanofluids and complex fluids used in thermal engineering applications.

3.5 | Thermo-Hydraulic Parameters

The thermo-hydraulic performance of the porous wavy microchannel is evaluated using several dimensionless engineering parameters, including the Nusselt number and friction factor. The average Nusselt number, which represents the convective heat transfer enhancement capability of the system, is defined in *Eq. (7)* as:

$$Nu = hD_h/k, \tag{7}$$

where h is the convective heat transfer coefficient, Dh denotes the hydraulic diameter, and k represents the thermal conductivity of the fluid. Higher values of the Nusselt number indicate stronger convective heat transfer performance inside the microchannel [22]. The friction factor, which characterizes the hydrodynamic resistance and pressure loss, is calculated using *Eq. (8)*:

$$f = 2\Delta P D_h/(\rho U_{in}^2 L), \tag{8}$$

where ΔP represents the pressure drop along the channel length, Uin is the inlet velocity, and L denotes the total length of the microchannel. The combined analysis of the Nusselt number and friction factor provides a comprehensive evaluation of the thermo-hydraulic performance of the porous wavy microchannel under different permeability conditions. The governing equations presented in this section are numerically solved to investigate the effects of porous medium permeability on the flow structure, temperature distribution, heat transfer enhancement, and friction characteristics of non-Newtonian nanofluid flow inside the wavy microchannel.

4|Numerical Method

The governing equations presented in the previous section were solved numerically using the Finite Element Method (FEM) to investigate the thermo-hydraulic behavior of non-Newtonian nanofluid flow inside the porous wavy microchannel. The numerical simulation was performed under steady-state, two-dimensional, and laminar flow conditions. The coupled continuity, momentum, and energy equations were simultaneously solved throughout the computational domain. The computational domain was discretized using non-uniform triangular elements in order to accurately capture the complex flow and thermal characteristics inside the corrugated microchannel geometry. A finer mesh distribution was employed near the channel walls and wavy regions where large velocity and temperature gradients were expected [9]. This mesh refinement improves the numerical accuracy of the solution and ensures proper prediction of the boundary layer behavior. The finite element formulation was implemented to discretize the governing equations described in *Eqs. (2)-(8)*. The discretized algebraic equations were iteratively solved until convergence was achieved for all dependent variables, including velocity components, pressure, and temperature fields. The convergence criterion for the numerical solution was defined based on the residual values of the governing equations. Convergence was assumed to be achieved when the relative error between two successive iterations became smaller than 10^{-6} for all variables. This strict convergence criterion ensures the numerical stability and reliability of the obtained results [11–14]. The SIMPLE algorithm was employed for pressure velocity coupling during the iterative solution process. Furthermore, second-order discretization schemes were utilized to improve the numerical accuracy of both momentum and energy transport equations. The thermo-physical properties of the non-Newtonian nanofluid were incorporated into the numerical model according to the governing rheological equations described previously. The porous medium effects were modeled through the Darcy-Brinkman formulation, which accounts for both permeability resistance and viscous diffusion effects inside the porous region. Appropriate boundary conditions were imposed throughout the computational domain. A uniform velocity profile and constant inlet temperature were specified at the channel inlet. At the outlet section, a pressure outlet boundary condition was applied. The upper and lower walls of the microchannel were subjected to constant wall temperature conditions. In addition, the no-slip condition was imposed along all solid boundaries [22].

4.1|Grid Independence Study

In order to ensure that the numerical results are independent of the computational mesh, a grid independence analysis was carried out using several mesh densities. Different structured and unstructured meshes with increasing element numbers were tested to evaluate their influence on the average Nusselt number and pressure drop. The numerical results obtained from different mesh configurations demonstrated that further mesh refinement beyond a certain number of elements produced negligible variations in the calculated thermo-hydraulic parameters. Therefore, the optimal mesh was selected based on the balance between computational accuracy and simulation time. The final computational mesh used in the present study provided stable numerical convergence and accurate prediction of velocity and temperature distributions inside the porous wavy microchannel [21].

4.2|Grid Independence Study

A grid independence analysis was conducted to ensure the numerical accuracy and stability of the present simulations. Three different mesh configurations were examined in order to investigate the influence of mesh density on the thermo-hydraulic characteristics of the non-Newtonian nanofluid flow inside the porous wavy microchannel. The average Nusselt number was selected as the primary evaluation parameter for the mesh sensitivity analysis because it directly reflects the heat transfer performance of the computational model. The obtained numerical results for different mesh configurations are summarized in *Table 1* [23].

Table 1. Variation of the average Nusselt number for different mesh configurations.

Mesh Configuration	Total Number of Elements	Average Nusselt Number
First mesh	250000	3.25
Second mesh	280000	3.85
Third mesh	300000	4.02

As observed in *Table 1*, increasing the mesh density improves the numerical prediction of the heat transfer characteristics inside the porous microchannel. The average Nusselt number increased from 3.25 for the first mesh configuration to 4.02 for the third mesh configuration. The difference between the second and third mesh configurations was relatively small, indicating that the numerical solution becomes nearly independent of mesh density at higher element numbers. Therefore, the third mesh configuration consisting of 300000 computational elements was selected for all simulations in the present study in order to achieve an appropriate balance between computational accuracy and simulation cost. The obtained results confirm the reliability and numerical stability of the present computational model for analyzing thermo-hydraulic transport phenomena inside porous wavy microchannels.

4.3 | Numerical Procedure

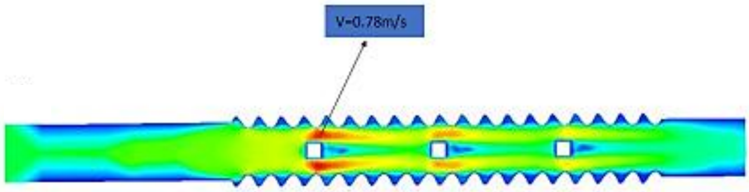
The numerical simulation procedure begins with defining the geometrical parameters and generating the computational mesh for the porous wavy microchannel. Subsequently, the governing equations together with the corresponding boundary conditions are discretized using the finite element approach. The iterative solution process is continued until the specified convergence criteria are satisfied for continuity, momentum, and energy equations. After convergence is achieved, the velocity field, pressure distribution, temperature contours, Nusselt number, and friction factor are extracted and analyzed to evaluate the thermo-hydraulic performance of the system [24]. The developed numerical methodology enables a detailed investigation of the effects of porous medium permeability on flow behavior, thermal transport characteristics, and pressure loss inside the non-Newtonian nanofluid-filled wavy microchannel.

5 | Results and Discussion

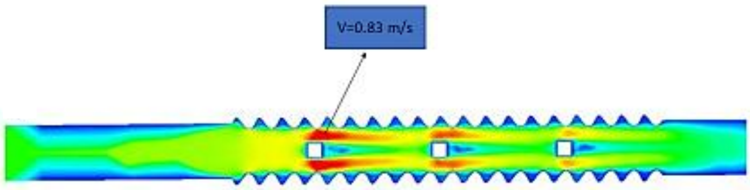
In this section, the thermo-hydraulic behavior of non-Newtonian nanofluid flow inside the porous wavy microchannel is comprehensively investigated under different permeability conditions. The effects of porous medium permeability on velocity distribution, temperature field, heat transfer enhancement, pressure drop, and friction characteristics are analyzed in detail. According to the thesis results, permeability plays a dominant role in controlling both the thermal and hydrodynamic behavior of the nanofluid flow inside the corrugated porous microchannel.

5.1 | Effect of Permeability on Velocity Distribution

The velocity contours of the non-Newtonian nanofluid for different permeability conditions are illustrated in *Fig. 1*. The obtained numerical results demonstrate that increasing permeability significantly enhances fluid motion inside the porous microchannel. As the permeability increases, the resistance force generated by the porous matrix decreases, allowing the nanofluid to penetrate more easily through the porous region. Consequently, the local velocity magnitude increases throughout the computational domain. According to the thesis results, the increase in permeability causes an increase in apparent fluid velocity under constant Reynolds number conditions due to variations in the effective viscosity of the non-Newtonian nanofluid. In contrast, lower permeability values intensify the resistance imposed by the porous matrix and suppress fluid motion near the corrugated walls. This behavior produces larger momentum dissipation and weaker circulation zones inside the microchannel. The sinusoidal geometry additionally generates local vortices and secondary flow structures near the wavy walls. These recirculation regions intensify fluid mixing and improve momentum transport inside the channel. The interaction between porous resistance and wall waviness significantly modifies the hydrodynamic structure of the flow field.



a.



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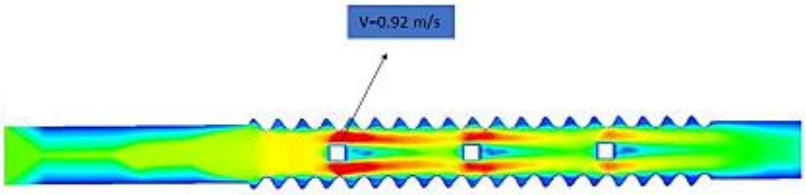

c.

Fig. 1. Velocity contours of the non-Newtonian nanofluid for different permeability conditions; a. low permeability, b. medium permeability, and c. high permeability.

5.2|Effect of Permeability on Temperature Distribution

Fig. 2 presents the temperature contours inside the porous wavy microchannel at different permeability conditions. The results reveal that permeability has a substantial influence on thermal transport and temperature distribution inside the channel. At low permeability values, the porous medium restricts fluid circulation and weakens convective heat transfer mechanisms. Consequently, higher temperatures are observed near the heated walls, resulting in thicker thermal boundary layers. As permeability increases, fluid circulation inside the porous region becomes stronger and thermal energy is transported more effectively throughout the channel. Therefore, the temperature gradients near the heated wall decrease, and a more uniform temperature distribution is obtained. According to the thesis findings, increasing fluid velocity inside the porous obstacles causes the fluid temperature to decrease more rapidly due to stronger convective transport mechanisms. Furthermore, the wavy geometry disrupts the thermal boundary layer development and enhances thermal mixing inside the microchannel. This mechanism improves the cooling performance compared with conventional straight channels.

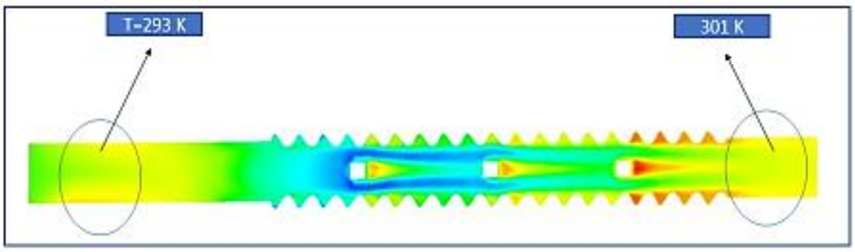

Fig. 2. Temperature contours inside the porous wavy microchannel for different permeability values.

5.3 | Variation of Average Nusselt Number

The variation of the average Nusselt number under different permeability conditions is illustrated in *Fig. 3*. The obtained numerical results demonstrate that the heat transfer performance inside the porous wavy microchannel is strongly influenced by the permeability of the porous medium. As permeability increases, the resistance force generated by the porous matrix decreases, allowing the nanofluid to circulate more effectively throughout the microchannel. This enhanced fluid motion improves convective heat transfer mechanisms and increases the average Nusselt number inside the channel. The enhancement in heat transfer performance is primarily associated with stronger fluid mixing, disruption of the thermal boundary layer, and improved interaction between the heated walls and the non-Newtonian nanofluid. Furthermore, the sinusoidal wavy geometry continuously disturbs the thermal boundary layer development and generates secondary flow structures near the corrugated walls, which significantly contribute to thermal enhancement. At lower permeability values, the porous medium imposes stronger resistance against fluid motion, resulting in weaker circulation regions and thicker thermal boundary layers near the heated surfaces. Consequently, the convective heat transfer rate decreases under low permeability conditions. The rheological behavior of the non-Newtonian nanofluid additionally affects the thermal transport characteristics through shear-dependent viscosity variations. These viscosity changes modify the local velocity gradients and influence the thermal diffusion mechanisms inside the porous microchannel. The obtained results confirm that increasing permeability improves the thermal performance of the porous wavy microchannel and enhances the cooling capability of the system through stronger convective transport mechanisms.

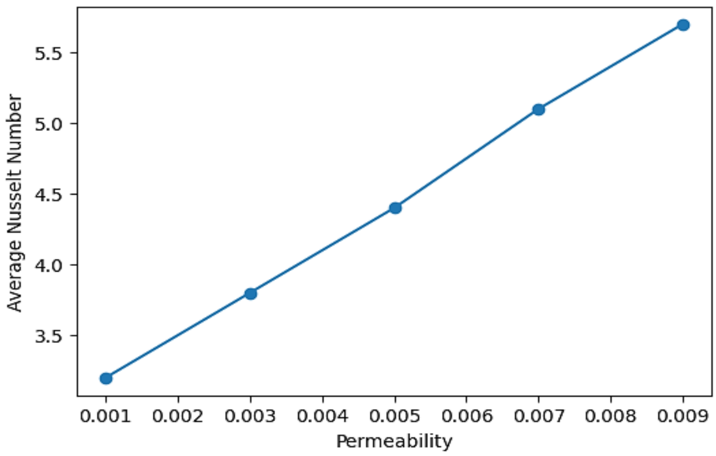

Fig. 3. Variation of average Nusselt number with permeability inside the porous wavy microchannel.

5.4 | Pressure Drop Characteristics

The effect of permeability on pressure drop is illustrated in *Fig. 4*. The results demonstrate that the pressure drop inside the porous microchannel is strongly influenced by porous resistance effects and flow intensity. At low permeability conditions, the Darcy resistance term becomes dominant and produces substantial pressure losses along the channel length. The porous matrix strongly opposes fluid motion, resulting in higher pumping power requirements. As permeability increases, the resistance force decreases, and the pressure drop is significantly reduced, facilitating smoother fluid transport through the porous structure. However, increasing the Reynolds number intensifies inertial forces and momentum interactions between the fluid, porous medium, and corrugated walls, leading to larger hydrodynamic losses inside the microchannel. Furthermore, the sinusoidal wavy geometry generates local flow disturbances and additional wall friction effects, which contribute to pressure loss enhancement. Although lower permeability may improve local thermal mixing, excessive flow resistance can negatively affect the overall thermo-hydraulic efficiency of the system. Therefore, an optimum permeability range is necessary to achieve a balance between heat transfer enhancement and pressure drop characteristics.

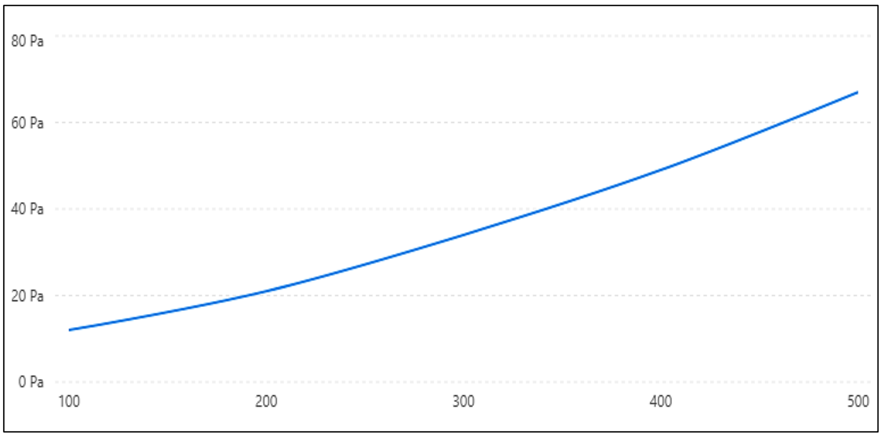

Fig. 4. Variation of pressure drop under different flow conditions.

5.5 | Friction Factor Analysis

The variation of the friction factor with permeability is presented in *Fig. 5*. The numerical results reveal that the friction factor decreases with increasing permeability. At lower permeability values, stronger porous resistance generates larger wall shear stress and momentum dissipation inside the channel, leading to higher friction factors. Conversely, increasing permeability reduces hydrodynamic resistance and facilitates smoother fluid motion through the porous matrix. Consequently, the friction factor decreases significantly. The rheological behavior of the non-Newtonian nanofluid also affects the friction characteristics because the apparent viscosity changes with local shear rate variations. The interaction between shear-dependent viscosity and porous resistance creates complex flow behavior inside the corrugated microchannel. The obtained results indicate that permeability is one of the most influential parameters governing the hydrodynamic performance of porous microchannel systems.

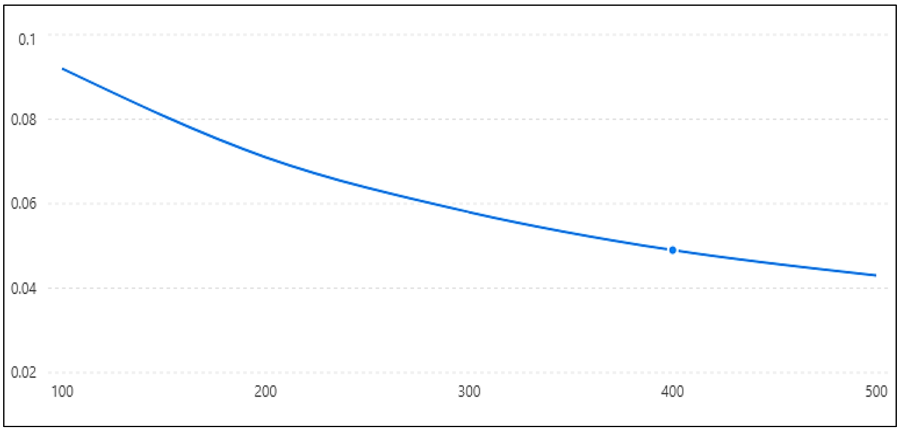

Fig. 5. Effect of permeability on friction factor.

6 | Conclusion

In the present study, the thermo-hydraulic behavior of non-Newtonian nanofluid flow inside a porous wavy microchannel was numerically investigated under different permeability conditions. The combined effects of porous medium resistance, sinusoidal wall geometry, and non-Newtonian fluid behavior on heat transfer enhancement and hydrodynamic characteristics were comprehensively analyzed using a two-dimensional numerical model based on the Darcy Brinkman formulation. The obtained numerical results demonstrated that permeability plays a critical role in controlling both the thermal and flow characteristics inside the porous microchannel. Increasing permeability reduced the resistance force generated by the porous matrix and facilitated smoother fluid motion throughout the channel. Consequently, higher fluid velocities and stronger convective transport mechanisms were achieved at larger permeability values. The temperature distribution results revealed that enhanced permeability improves thermal transport and weakens the thermal boundary layer development near the heated walls. The interaction between the porous structure and the sinusoidal wavy geometry intensified fluid mixing and significantly improved the overall heat transfer performance of the microchannel system. The analysis of the average Nusselt number indicated that heat transfer enhancement increases with increasing permeability due to stronger circulation and improved convective heat transfer mechanisms inside the porous medium. In addition, the wavy geometry contributed to thermal enhancement through continuous disruption of the thermal boundary layer and generation of local secondary flow structures.

The pressure drop analysis showed that lower permeability conditions produce substantially larger hydrodynamic losses because of stronger Darcy resistance effects. The porous matrix strongly opposes fluid motion at low permeability values, resulting in higher pumping power requirements and increased friction effects inside the channel. Furthermore, the friction factor results demonstrated that the hydrodynamic resistance decreases with increasing permeability and Reynolds number. The rheological characteristics of the non-Newtonian nanofluid additionally influenced the velocity distribution and wall shear stress behavior inside the porous wavy microchannel. The present numerical investigation confirmed that the combined utilization of porous media, sinusoidal wavy microchannel geometry, and non-Newtonian nanofluids can considerably enhance the thermo-hydraulic performance of advanced micro-scale cooling systems. The obtained findings provide valuable insight into the design and optimization of compact thermal management devices used in microelectronic cooling systems, MEMS technologies, compact heat exchangers, and other high-performance thermal engineering applications. Finally, it is recommended that future investigations focus on transient flow behavior, three-dimensional numerical simulations, magnetic field effects, nanoparticle concentration variations, and slip-flow conditions in order to achieve a deeper understanding of thermo-fluid transport phenomena inside porous microchannel systems.

Authors' Contributions

The author solely conducted the research and prepared the manuscript and has approved its final version.

Data Availability

The data are available from the corresponding author upon reasonable request.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The author confirms consent for the publication of this work.

Ethics Approval and Consent to Participate

This article does not include experiments involving humans or animals.

References

[1] Rosa, P., Karayiannis, T. G., & Collins, M. W. (2009). Single-phase heat transfer in microchannels: The importance of scaling effects. *Applied Thermal Engineering*, *29*(17–18), 3447–3468. https://doi.org/10.1016/j.applthermaleng.2009.05.015

[2] Karniadakis, G., Beskok, A., & Aluru, N. (2005). *Microflows and nanoflows: Fundamentals and simulation*. Springer. https://doi.org/10.1007/0-387-28676-4_15

[3] McGlen, R. J., Jachuck, R., & Lin, S. (2004). Integrated thermal management techniques for high power electronic devices. *Applied Thermal Engineering*, *24*(8–9), 1143–1156. https://doi.org/10.1016/j.applthermaleng.2003.12.029

[4] International Technology Roadmap for Semiconductors (ITRS). (2005). *International technology roadmap for semiconductors*. https://www.semiconductors.org/wp-content/uploads/2018/08/2005Assembly-Packaging.pdf

[5] Kandlikar, S. (2006). *Heat transfer and fluid flow in minichannels and microchannels*. Elsevier. https://doi.org/10.1016/B978-0-08-044527-4.X5000-2

[6] Azizi, Z., Alamdari, A., & Malayeri, M. R. (2015). Convective heat transfer of Cu--water nanofluid in a cylindrical microchannel heat sink. *Energy Conversion and Management*, *101*, 515–524. https://doi.org/10.1016/j.enconman.2015.05.073

[7] Akbarinia, A., Abdolzadeh, M., & Laur, R. (2011). Critical investigation of heat transfer enhancement using nanofluids in microchannels with slip and non-slip flow regimes. *Applied Thermal Engineering*, *31*(4), 556–565. https://doi.org/10.1016/j.applthermaleng.2010.10.017

[8] Toh, K. C., Chen, X. Y., & Chai, J. C. (2002). Numerical computation of fluid flow and heat transfer in microchannels. *International Journal of Heat and Mass Transfer*, *45*(26), 5133–5141. https://doi.org/10.1016/S0017-9310(02)00223-5

[9] Ramiar, A., & Ranjbar, A. A. (2011). Effect of viscous dissipation and variable properties on nanofluids flow in two dimensional microchannels. *International Journal of Engineering*, *24*(2), 131–142. https://www.ije.ir/article_71900.html

[10] Amani, J., & Abbasian Arani, A. A. (2014). Experimental study on heat transfer and pressure drop of TiO2-water nanofluid. *Amirkabir Journal of Mechanical Engineering*, *46*(1), 79-88. (**In Persian**). https://doi.org/10.22060/mej.2014.344

[11] Zhou, Y., Zhang, R., Staroselsky, I., Chen, H., Kim, W. T., & Jhon, M. S. (2006). Simulation of micro-and nano-scale flows via the lattice Boltzmann method. *Physica A: Statistical Mechanics and Its Applications*, *362*(1), 68–77. https://doi.org/10.1016/j.physa.2005.09.037

[12] Sheikhpour, N., Lavasani, A. M., & Salehi, G. (2025). Numerical investigation of the magneto-hydraulic-thermal performance of a nanofluid in a semi-porous wavy channel. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *239*(5), 1766–1777. https://doi.org/10.1177/09544062241293354

[13] Leondes, C. T. (2007). *Mems/Nems:(1) Handbook techniques and applications design methods,(2) Fabrication techniques,(3) manufacturing methods,(4) Sensors and actuators,(5) Medical applications and MOEMS*. Springer Science & Business Media. https://content.e-bookshelf.de/media/reading/L-340003-794df3f34e.pdf

[14] Mehendale, S. S., Jacobi, A. M., & Shah, R. K. (2000). Fluid flow and heat transfer at micro-and meso-scales with application to heat exchanger design. *Applied Mechanics Reviews*, *53*(7), 175–193. https://doi.org/10.1115/1.3097347

[15] Anoop, K., Sadr, R., Yu, J., Kang, S., Jeon, S., & Banerjee, D. (2012). Experimental study of forced convective heat transfer of nanofluids in a microchannel. *International Communications in Heat and Mass Transfer*, *39*(9), 1325–1330. https://doi.org/10.1016/j.icheatmasstransfer.2012.07.023

[16] Xuan, Y., & Roetzel, W. (2000). Conceptions for heat transfer correlation of nanofluids. *International Journal of Heat and Mass Transfer*, *43*(19), 3701–3707. https://doi.org/10.1016/S0017-9310(99)00369-5

[17] Qu, W., & Mudawar, I. (2002). Analysis of three-dimensional heat transfer in micro-channel heat sinks. *International Journal of Heat and Mass Transfer*, *45*(19), 3973–3985. https://doi.org/10.1016/S0017-9310(02)00101-1

[18] Kroeker, C. J., Soliman, H. M., & Ormiston, S. J. (2004). Three-dimensional thermal analysis of heat sinks with circular cooling micro-channels. *International Journal of Heat and Mass Transfer*, *47*(22), 4733–4744. https://doi.org/10.1016/j.ijheatmasstransfer.2004.05.028

[19] Kou, H. S., Lee, J. J., & Chen, C. W. (2008). Optimum thermal performance of microchannel heat sink by adjusting channel width and height. *International Communications in Heat and Mass Transfer*, *35*(5), 577–582. https://doi.org/10.1016/j.icheatmasstransfer.2007.12.002

[20] Foong, A. J. L., Ramesh, N., & Chandratilleke, T. T. (2009). Laminar convective heat transfer in a microchannel with internal longitudinal fins. *International Journal of Thermal Sciences*, *48*(10), 1908–1913. https://doi.org/10.1016/j.ijthermalsci.2009.02.015

[21] Ghazvini, M., & Shokouhmand, H. (2009). Investigation of a nanofluid-cooled microchannel heat sink using Fin and porous media approaches. *Energy Conversion and Management*, *50*(9), 2373–2380. https://doi.org/10.1016/j.enconman.2009.05.021

[22] Kumar, P., Dwivedi, R., & Pandey, K. M. (2024). Hybrid-nanofluid flow through partially porous wavy channels: thermo-hydraulic performance and entropy analysis. *Heat Transfer Engineering*, *45*(3), 211–232. https://doi.org/10.1080/01457632.2023.2185487

[23] Abdollahzadehsangroudi, M., Francisco, M., Lopes, R., Dolati, F., Pascoa, J. C., & Rodrigues, F. (2024). Insight into porous fin microchannel heat sinks with improved thermo-hydraulic performance. *Physics of Fluids*, *36*(4), 042015-1–15. https://doi.org/10.1063/5.0198294

[24] Niknejad, K., Sharifzadeh Baei, M., & Motallebi Tala Tapeh, S. (2018). Synthesis of Metformin Hydrochloride nanoliposomes: Evaluation of physicochemical characteristics and release kinetics. *International Journal of Nano Dimension*, *9*(3), 298–313. https://ijnd.tonekabon.iau.ir/article_659887.html