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Review Article

Studying Non-Newtonian Fluid Dynamics: Axisymmetric Channel Flow with Porous Walls

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Abstract

A fascinating field for study and application is the complex interaction between non-Newtonian fluid behavior and porous barriers in axisymmetric channel flows. This brief overview explores the field of non-Newtonian fluid dynamics in axisymmetric channels, where the complexity created by porous walls affects transport phenomena, mixing efficiency, and flow patterns. Through a review of recent developments in computational modelling and experimental studies, this paper offers a concise summary of the main conclusions, difficulties, and possible uses in this emerging discipline. This work is important for many fields, such as chemical engineering, biomedical technology, and environmental sciences. It provides a promising technique to use the unique properties of non-Newtonian flows for useful innovation.

Keywords: Non-Newtonian Fluid Dynamics, Axisymmetric Channel Flow, Porous Walls, Transport Phenomena

Introduction

From the lowest scale of molecular interactions to the largest scale of planetary motion, fluid dynamics governs phenomena and is a fundamental concept in our knowledge of the complex workings of nature (Golibrzuch, Bartels, Auerbach, & Wodtke, 2015). Newtonian fluids are defined by a linear connection between shear stress and shear rate. The foundation for understanding this behavior was established in the 17th century by Sir Isaac Newton's description of viscous flow (Zeytounian & Zeytounian, 2017). But simplicity is rarely the rule in nature, and many fluids behave in ways that are inconsistent with Newton's equation of viscosity (Bonn, Denn, Berthier, Divoux, & Manneville, 2017). These "non-Newtonian fluids" include a wide range of materials, such as blood, magma, suspensions, and polymer solutions (Bellout, Bloom, Bellout, & Bloom, 2014). Their viscosity's nonlinearity creates complications that make conventional methods for understanding fluid dynamics difficult to apply (Ershadnia et al., 2020; Squires & Mason, 2010). In all of this intricacy, one area of great importance is the interplay between restricting geometries and non-Newtonian fluids (Booth, Roering, & Rempel, 2013). The movement of non-Newtonian fluids through axisymmetric channels with porous walls is one example of such a situation (Cheng, Ning, & Dai, 2020). The existence of porous walls creates a complex web of flow patterns, transport phenomena, and mixing dynamics by introducing an intricate interplay between fluid rheology and boundary features (Dharmendra Tripathi & Bég, 2013). Investigating these phenomena is not just a fluid mechanics academic endeavor; it has the potential to transform a variety of industries, including the energy and medical fields (Coccia, 2020).

Beyond the confines of academia, non-Newtonian fluid dynamics in axisymmetric tubes with porous walls is of great importance (Yasodhara, Sreenadh, Sumalatha, & Srinivas, 2020). Numerous disciplines, including as petroleum engineering, chemical processing, environmental research, and biomedicine, use these flows (Gerami et al., 2019). For example, in the field of petroleum reservoir engineering, improved oil recovery techniques can be impacted by knowledge of how non-Newtonian fluids move through porous rock formations (Lohne, Nødland, Stavland, & Hiorth, 2017). The complex mixing patterns found in microchannels may provide the secret to effective medication delivery devices in the field of biomedicine.

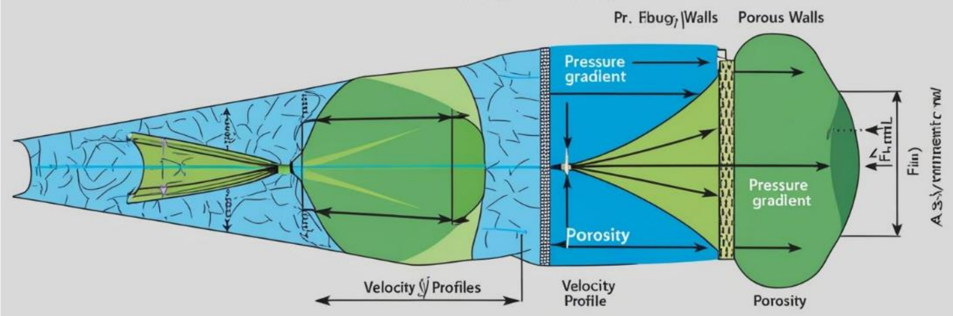

Figure 1. Non-Newtonian fluid dynamics

The axisymmetric arrangement, which is defined by rotational symmetry around a central axis, is especially interesting since it is seen in many artificial and natural systems (Klughammer et al., 2018). Asymmetries in channels with porous walls, from microfluidic devices in labs to geological flows in subterranean reservoirs, are not only encountered but also increasingly utilized for their distinct flow characteristics. These channels show a wide variety of flow regimes, each having unique characteristics driven by fluid qualities, porous wall characteristics, and flow rate. The behavior of non-Newtonian fluids in axisymmetric channels with porous walls must therefore be understood and predicted using a multidisciplinary approach that integrates fluid mechanics, rheology, porous media theory, and numerical simulations (Chiapponi, Petrolo, Lenci, Di Federico, & Longo, 2020).

We explore the fascinating field of non-Newtonian fluid dynamics in axisymmetric channels with porous walls in this brief study. Our goal is to present a thorough summary of current advancements in this quickly developing field, emphasizing the most important discoveries, difficulties, and possible uses. By combining theoretical understanding, computational modelling, and experimental data, we aim to clarify the complexities of fluid behavior in this intricate situation (Weber, Mancini, Schaffel-Mancini, & Kupka, 2013). The following sections explore the governing equations of these flows, clarify the different flow regimes that arise, talk about how flow patterns affect mixing efficiency, tackle modelling and characterization challenges, and offer a peek of the exciting applications that still need to be investigated.

Through our analysis of the state-of-the-art of non-Newtonian fluid dynamics in axisymmetric channel flows with porous walls, we want to further our understanding of this complex phenomenon and open up new avenues for future research (D Tripathi & Bég, 2014). We are on the verge of delving deeper into the behavior of these intriguing fluids inside confined geometries, which will enable new applications across a wide range of scientific and engineering fields, as interdisciplinary collaborations continue to flourish and computational techniques advance.

2. Governing Equations and Flow Regimes

A thorough understanding of the governing equations that regulate the flow behavior is essential to comprehending the complexities of non-Newtonian fluid dynamics within axisymmetric channels with porous walls (Premlata, Tripathi, Karri, & Sahu, 2017). Although the Navier-Stokes equations provide a fundamental framework for explaining fluid motion, constitutive relationships that represent the distinctive rheological features of non-Newtonian fluids must be incorporated due to their complexity.

The flow regimes observed in axisymmetric channels with porous walls are considerably affected by the addition of non-Newtonian constitutive equations (Panaseti & Georgiou, 2017). Shear stress and shear rate have a nonlinear connection depending on the fluid's unique rheological behavior, which can include viscoelasticity, shear-thinning, or shear-thickening. Because of this nonlinearity, a wide range of flow patterns and behaviors are produced, which differ greatly from the behaviors seen in Newtonian fluids.

These channels' flow regimes can be divided into groups according to the characteristics of the porous wall, the fluid properties, and the flow rates. Laminar flow, which is characterized by smooth, ordered streamlines, may predominate at lower flow rates and under specific non-Newtonian conditions (De, Kuipers, Peters, & Padding, 2017). A shift to turbulent or transitional flow, characterized by complex flow patterns, vortex formation, and enhanced mixing, may happen when flow rates rise. A further layer of complexity is introduced by the interaction between wall permeability and fluid rheology, which further alters these flow regimes.

The boundary layers that form close to the porous walls are where the impacts of wall permeability are most noticeable. These boundary layers interact with the fluid's intrinsic rheological behavior in addition to affecting mass and momentum transmission (Monroy, 2017). The fluid experiences changes in pressure, velocity, and shear stress distributions as it moves through the porous media, which results in complex changes to the flow patterns. By stimulating the formation of secondary flows and vortices, the porous walls may significantly alter the fluid's dynamics.

Furthermore, unanticipated phenomena might arise from the interaction of viscous forces, inertia, and the fluid's non-Newtonian rheological features (Chhabra, 2010). Examples include the formation of flow instabilities that result in chaotic behavior and the appearance of plug-like flow profiles, where the fluid travels in discrete parts as opposed to a continuous flow.

The coexistence of these several flow regimes introduces levels of complexity into the domain of axisymmetric channels with porous walls that defy our comprehension and modelling abilities. One of the ongoing challenges is to accurately forecast the transition points between these regimes and quantify their influence on transport parameters (Zhao & Yang, 2013). However, new developments in computational fluid dynamics combined with improved experimental methods have given important new understandings of the complex relationship between fluid rheology, wall permeability, and flow behavior.

We address several particular instances of these flow regimes in the following sections, examining the unique features they display and their consequences for mixing efficiency and transport phenomena. Through analyzing the interplay between non-Newtonian fluid dynamics and porous barriers in the axisymmetric setting, we aim at provide a thorough synopsis of the state of the art in this fascinating area.

3. Flow Patterns and Mixing Enhancement

In axisymmetric channels, the interaction of porous walls with non-Newtonian fluid behavior results in complex flow patterns that have a major impact on mixing dynamics and transport efficiency (Crespí-Llorens, Vicente, & Viedma, 2016). The porous nature of the channel walls and the special rheological characteristics of non-Newtonian fluids result in intricate interactions that mould the velocity and shear rate distributions throughout the channel cross-section.

In laminar flow regimes, surprising occurrences can arise from non-Newtonian behaviors in fluid motion in smooth layers (Hosseini, Omidvar, Kheirkhahan, & Farzin, 2019). For example, fluids that are shear-thinning show a drop in viscosity as the shear rate increases. The fluid close to the wall encounters a higher shear rate and a lower viscosity, which promotes accelerated flow in the near-wall region. This feature gives rise to a phenomenon called velocity inversion. This type of behavior affects the concentration gradients and, in turn, the velocity profiles across the channel, which in turn affects the mass transport mechanisms.

The porous walls play an important role in promoting mixing efficiency as flow rates rise and the flow regimes change to turbulent or transitional. The impact of non-Newtonian behavior intensifies the already intricate flow patterns present in these regimes (Malkin, 2013). Velocity gradients are caused by the non-uniform viscosity distribution over the channel cross-section, and this might potentially result in increased transverse mixing. This phenomenon is especially important in microfluidic applications, like chemical reactors or lab-on-a-chip systems, where exact control over mixing is crucial.

There are more ways to improve mixing when there are permeable barriers present. In addition to eddies and secondary flows, the convective movement of fluid through the porous material produces vortices that interact with the bulk fluid motion (Haller, Hadjighasem, Farazmand, & Huhn, 2016). Concentration fields can be homogenized more easily when fluid parcels with different properties are mixed together thanks to these flow characteristics. For chemical reactions, mass transfer, and heat exchange processes taking place within the channel, this mixing improvement is quite helpful.

Moreover, new mixing modes may emerge from the interaction of porous walls with non-Newtonian rheology. Similar to the mixing mechanism in viscoelastic flows, the non-uniform distribution of viscosity across the channel can cause differential fluid velocities, which can lead to the stretching and folding of fluid layers (Pandey & Chaube, 2010). These complex flow behaviors present new possibilities for customizing mixing schemes and streamlining transport procedures for particular uses.

Recent developments in experimental methods, such as microfluidic visualization and particle image velocimetry (PIV), have made it possible for researchers to see and measure these flow patterns firsthand (Williams, Park, & Wereley, 2010). These methods, when combined with computer simulations that accurately depict the intricate fluid-wall interactions, have improved our comprehension of how non-Newtonian fluids move in axisymmetric channels with porous walls.

We discuss particular instances of these flow patterns in the following sections, showing how non-Newtonian fluid dynamics and porous barriers are coupled in practice. We hope to shed light on how this interaction might be used to improve industrial processes and create more effective microfluidic devices by examining the consequences of these flow patterns for mixing enhancement and transport phenomena.

4. Challenges and Future Directions

Even though studying non-Newtonian fluid dynamics in axisymmetric channels with porous walls has produced important discoveries, there are still a number of issues that need to be addressed and provide exciting directions for further study (Rafiq, Abbas, Sheikh, & Hasnain, 2020). Understanding and modelling these flows requires a multifaceted approach due to the intricate interplay between wall permeability and fluid rheology.

Precisely describing the rheological characteristics of non-Newtonian fluids is a major difficulty. Characterizing these properties can be challenging due of their great sensitivity to many parameters like pressure, temperature, and shear history. Acquiring trustworthy experimental data for non-Newtonian behavior is still a challenge that requires both creative measurement strategies and strong data processing methodologies, particularly in intricate flow configurations (Ghalambaz, Ayoubi Ayoubloo, & Hajjar, 2020).

Another problem is modelling the complex interactions between non-Newtonian fluids and porous barriers. The combined impacts of wall permeability, flow-induced modifications to the porous media structure, and fluid rheology must be taken into consideration in numerical simulations. It is still a work in progress to create precise and computationally effective models that encompass the entire spectrum of flow regimes, from laminar to turbulent (Farooq, Shah, Shutaywi, Bonyah, & Roy, 2020). Furthermore, a major challenge is integrating these models with experimental data to validate and improve predictions.

The process of translating results from laboratory-scale studies to practical applications involves intricate considerations of boundary conditions, geometry, and fluid characteristics. For the results to be applicable, it is important to carefully analyze how different wall permeabilities, fluid viscosities, and channel dimensions affect flow behavior (Dey & Sekhar, 2016). A comprehensive strategy that takes these scale-dependent effects into account is needed to close the gap between basic discoveries and useful applications.

Moreover, non-Newtonian flow dynamics in axisymmetric channels with porous walls can be highly affected by three-dimensional effects, particle interactions, and flow pulsations. Future research should continue to focus on examining these extra complexities and how they affect flow patterns, mixing effectiveness, and transport phenomena (A. Ali, Farooq, Abbas, Bukhari, & Fatima, 2020).

Creating predictive tools to direct engineering design and optimization should be a priority for future research areas. Through the identification of relationships between fluid properties, characteristics of porous walls, and flow behavior, researchers can offer practitioners recommendations for customizing channel designs and operating circumstances in order to attain desired results (Qayyum, Khan, Rahim, & Ullah, 2015).

The possible uses of non-Newtonian fluid dynamics in axisymmetric channels with porous walls are numerous and fascinating, but they also present obstacles. Drug delivery systems, chemical reactions, and enhanced oil recovery are just a few fields that stand to gain from a better comprehension of these fluxes (Roustaei & Frigaard, 2013). Customizing flow patterns and mixing dynamics for particular applications necessitates an integrated approach combining modern computational tools, fluid mechanics, rheology, and porous media theory (N. Ali, Ullah, & Rasool, 2020).

In the next chapters, we examine the emerging fields that could profit from this work and discuss the complexities of applying non-Newtonian fluid dynamics for innovative applications in axisymmetric channels with porous walls. We aim to provide the foundation for a future where these complex flow dynamics are used to open up new vistas for fluid-based technologies and processes by tackling the opportunities and challenges concurrently.

5. Applications

The complex interaction between porous walls and non-Newtonian fluid dynamics in axisymmetric channels provides a wide range of applications in scientific and industrial domains. These scenarios offer great potential for process optimization, efficiency gains, and the development of novel technologies due to the distinct flow patterns, mixing efficiencies, and transport dynamics that emerge.

5.1. Enhanced Oil Recovery: The field of petroleum engineering is one of the most important applications. The porous rock formations seen in oil reserves are modelled by axisymmetric channels with porous walls. Designing enhanced oil recovery solutions requires an understanding of the interactions between non-Newtonian fluids and these formations (Druetta, Raffa, & Picchioni, 2019). The complex interplay between fluid rheology and porous medium characteristics can result in decreased viscous fingering, increased sweep efficiency, and more effective use of reservoir resources.

5.2. Microfluidic Devices: In the field of microfluidics, where exact manipulation of fluid dynamics is critical, non-Newtonian fluid dynamics in axisymmetric tubes present enormous promise (Khali, Nebbali, Ameziani, & Bouhadef, 2013). It is possible to precisely control mixing patterns, improve particle transport, and build effective lab-on-a-chip devices by manipulating non-Newtonian behaviors. These instruments are used in chemical analysis, biological research, and medical diagnostics.

5.3. Environmental Remediation: In environmental cleanup, the capacity to control fluid flow and movement inside porous material is useful (Yan, Lien, Koel, & Zhang, 2013). Because of their complicated flow patterns and increased mixing, non-Newtonian fluids can be used to better remove contaminants from porous surfaces by facilitating the mobilization and extraction of pollutants from groundwater and soil.

5.4. Chemical Processing: Complex fluid dynamics are involved in many chemical processes, from reaction engineering to polymer synthesis (Cambie, Bottecchia, Straathof, Hessel, & Noel, 2016). Porous-walled axisymmetric tubes provide a platform for maximizing mixing and reaction efficiency. Researchers can better control reaction kinetics and product yields by adjusting the channel design and choosing suitable non-Newtonian fluid characteristics.

5.5. Biomedical Engineering: For biological applications, the impact of non-Newtonian behaviors in porous channels is significant (Foong, Shirani, Toghraie, Zarringhalam, & Afrand, 2020). For example, in medication delivery systems, exact drug release profiles can be achieved by taking use of the distinct flow patterns and mixing dynamics. Furthermore, by comprehending the interactions between non-Newtonian fluids and biological tissues, medical procedures can be optimized and blood flow in vessels can be modelled.

5.6. Geophysical Flows: There are geophysical contexts where studying axisymmetric channel flows with porous walls is relevant, such as magma movement in volcanic conduits (Gudmundsson, 2012). Determining how non-Newtonian characteristics affect the dynamics of these flows can help forecast volcanic activity and lessen related risks.

5.7. Enhanced Mixing and Heat Transfer: These channels' complex flow patterns and improved mixing present opportunities for heat exchangers, where effective mixing can result in higher heat transfer rates (Alam & Kim, 2018). Applications ranging from industrial processes to energy-efficient HVAC systems are affected by this.

Multidisciplinary partnerships are becoming more important than ever as the field develops. To understand the intricacies of non-Newtonian fluid dynamics inside axisymmetric channels with porous walls, researchers from fluid dynamics, porous media, rheology, and other application fields must collaborate. We can leverage the potential of these complex flows to develop novel solutions that advance industry, society, and scientific understanding by connecting theoretical ideas, computer modelling, and experimental validations.

6. Conclusion

Investigating non-Newtonian fluid dynamics in axisymmetric channels with porous walls has revealed an intriguing domain of fluid behavior that contradicts standard theories. Transport phenomena, mixing dynamics, and flow patterns are shaped by the intricate interactions between wall permeability and fluid rheology. The topic of enhanced oil recovery includes numerous applications and scientific disciplines, ranging from the macroscopic domain to the microscale complexities of microfluidic devices. This small review has brought attention to the field's significance. Through analyzing the governing formulas, figuring out flow patterns, and exploring the intricacies of mixing enhancement, we have explored the diverse terrain of non-Newtonian flows in axisymmetric channels. It is clear from the difficulties we have faced and the possible uses we have investigated that this field presents chances to rethink procedures, enhance technological capabilities, and expand scientific knowledge. However, the trip is far from over. Research is still ongoing to address the difficulties in precisely describing non-Newtonian behaviors, creating prediction models, and translating discoveries to real-world applications. The possibility for deeper insights and more precise forecasts appears promising as computational capabilities and experimental approaches continue to advance. Interdisciplinary cooperation is essential to this inquiry and understanding process. To fully understand the complexities of non-Newtonian fluid dynamics inside axisymmetric channels with porous walls, researchers in the fields of fluid mechanics, rheology, porous media theory, computational simulations, and a wide range of application domains must continue to collaborate. I want to stress again that this discipline encompasses much more than just academic study as I wrap up this brief overview. It is a doorway to innovations that have the power to transform sectors, enhance workflows, and advance scientific understanding. Through embracing these complex flows' complexities, challenges, and opportunities, researchers are poised to make ground-breaking discoveries that will transform technology and increase our understanding of fluid behavior for years to come.

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