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Research Article

FLUID DYNAMICS SIMULATION OF MICROFLOWS IN MICROFLUIDIC DEVICES

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Abstract

This study explores fluid dynamics in micro-scale flows within microfluidic devices, which exhibit unique characteristics distinct from those observed in macroscale systems. The primary objective of this research is to analyze and simulate fluid flow behavior using numerical methods while assessing the influence of device design parameters on flow performance. The study adopts a qualitative descriptive approach, employing data collection methods such as interviews, direct observations, and documentation analysis. Through comprehensive analysis, the results reveal that microfluidic flow is highly sensitive to channel geometry and various physical factors, particularly fluid viscosity and surface tension. These factors significantly alter flow patterns, velocity distribution, and overall fluid behavior within microchannels. The study also identifies how design variations can either enhance or hinder fluid transport efficiency, depending on their alignment with the intrinsic properties of microfluidic systems. Simulations performed during the study further confirm the nonlinear interactions between channel dimensions and fluid properties, emphasizing the importance of precise calibration during the design process. Based on these findings, the study recommends design optimization strategies that prioritize not only functional performance but also stability and reliability in microfluidic operations. The insights provided are expected to contribute to the development of more effective microfluidic devices, particularly for applications in biomedical diagnostics, chemical analysis, and lab-on-a-chip systems. Overall, this research highlights the critical role of microfluidic design considerations in achieving accurate and efficient fluid control at the microscale.

Keywords: Fluid Dynamics, Microfluidic, Numerical Simulation

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INTRODUCTION

Fluid flow within microfluidic devices exhibits unique characteristics that significantly differ from flow behavior at the macroscale (Anshory & Wisaksono, 2022; Behera, 2022; Gharat dkk., 2024). At the microscale, viscosity and surface tension often become dominant factors influencing flow dynamics (Sadasivan dkk., 2025; Yang dkk., 2025; Zega & Gea, 2025). These phenomena make microfluidic flow highly sensitive to minor variations in geometry and operating conditions. With ongoing technological advancements, microfluidic devices have found increasing applications in fields such as biotechnology, chemical analysis, and medical diagnostics. However, a deeper understanding of microfluidic flow dynamics and accurate simulation methods remains limited, particularly regarding how various design parameters influence fluid behavior at the microscale. This study aims to address this challenge by providing a simulation model capable of more accurately capturing fluid dynamics in microfluidic systems.

Although numerous studies have attempted to develop models for microfluidic flow, the majority of them still concentrate on macroscale applications and fail to fully address the significant differences present at the microscale. Most existing research relies on expensive experimental approaches, which often lack flexibility in accommodating diverse design variations. In contrast, numerical simulations offer substantial potential to overcome these limitations by providing tools for faster and more efficient fluid flow modeling (Ferhath & Kasi, 2025; Lancmanová & Bodnár, 2025; Li dkk., 2025). However, simulating fluid flow in microfluidic devices frequently encounters major challenges in achieving high accuracy, especially when dealing with nonlinear factors and the geometric complexities of microchannels. Therefore, this study seeks to fill this knowledge gap by developing a more comprehensive numerical simulation approach.

The primary objective of this research is to analyze and simulate fluid flow in microfluidic devices using appropriate numerical methods to accurately represent fluid dynamic phenomena. Additionally, the study aims to assess the influence of various microfluidic design parameters—such as channel structure, geometry, and boundary conditions—on fluid behavior at the microscale. Through in-depth simulations, this study is expected to yield new insights into how microfluidic device designs can be optimized to enhance efficiency and performance in fluid-sensitive applications. The outcomes of these simulations will also serve as practical guidance for engineers and researchers in optimizing the design and operation of microfluidic devices for a wide range of applications.

The hypothesis of this study is that numerical simulation can serve as an effective and accurate tool for modeling fluid flow in microfluidic devices, despite the inherent complexity posed by the microscale. The research posits that, with an appropriate approach, simulations can provide a clearer understanding of how different design parameters influence fluid flow at the microscale, and how microfluidic systems can be optimized for various applications. Based on this rationale, the research is deemed necessary, as its results will not only deepen the understanding of fluid flow dynamics in microfluidic systems but also offer practical contributions to the design and operation of such devices in industrial and research settings.

Fluid dynamics is a branch of fluid mechanics that studies the movement of fluids and the forces acting upon them (Ahmad dkk., 2024; Rabbany dkk., 2024; Taufiq & Kaniawati, 2023). Generally, fluid dynamics involves the analysis of how fluids behave under the influence of various external factors such as friction, pressure, and gravity (Herho & Suwarman, 2024; Khambali dkk., 2025; Syakila dkk., 2025). In this context, fluids can be categorized into two main types: ideal fluids (which are non-viscous) and real fluids (which exhibit viscosity). The fundamental law used to describe fluid dynamics is the Navier–Stokes equation, which defines the relationship among fluid velocity, pressure, and viscosity in a dynamic system (Pandey dkk., 2025; Siddqi, 2024; Takabe, 2024). A comprehensive understanding of fluid dynamics is essential for numerous applications, particularly in the design of increasingly prevalent microfluidic devices.

Fluid dynamics can be classified into several manifestations depending on the nature and scale of motion. One of the key classifications in fluid dynamics is between laminar and turbulent flows. Laminar flow occurs when fluid moves smoothly and orderly, typically at low velocities or in narrow channels, such as those found in microfluidic systems. Conversely, turbulent flow occurs at higher velocities and is characterized by chaotic fluid movement. Additionally, fluid flow can be categorized based on the compressibility of the fluid—namely, incompressible and compressible flow. In microfluidic contexts, incompressible flow is more common, as fluid movement at the microscale generally does not significantly affect fluid volume or mass.

Microfluidics is a field that focuses on the study and design of devices capable of controlling fluid flow at the microscopic scale, typically involving channel dimensions smaller than 1 mm (Abdi dkk., 2024; Mukherjee dkk., 2024). These microfluidic devices are designed to handle extremely small volumes of fluid, often in the nanoliter or even picoliter range, with the goal of facilitating various applications such as biotechnological analysis, chemical sensing, and drug development. One of the main advantages of these devices is their ability to manipulate fluids at such a small scale, enabling faster, cheaper, and more efficient experimental and process execution. Moreover, better control over fluid flow allows for more precise measurements and process control, particularly in medical and laboratory applications.

Microfluidic devices encompass a wide range of types and functionalities, which can be distinguished based on their operational principles and specific applications. Some examples of microfluidic devices include microchannels that utilize capillary action to transport fluids, as well as systems that rely on external pressure or electrokinetic forces for fluid movement. Other types, such as lab-on-a-chip devices, are designed to integrate various analytical and experimental functions into a single small chip. These devices hold significant promise in fields ranging from medical diagnostics and chemical analysis to biotechnological experiments, owing to their capability for rapid and efficient microfluidic processing.

Numerical simulation is a computational technique used to model and analyze physical phenomena that are difficult or impossible to observe directly (Araújo dkk., 2023; Gautheron dkk., 2024). In the context of fluid dynamics, numerical simulation is employed to solve the equations governing fluid flow—particularly the Navier–Stokes equations, which are too complex to solve analytically (Satrio dkk., 2025; Yamin dkk., 2024). Numerical simulation techniques allow researchers to model various fluid flow scenarios under different conditions, such as laminar or turbulent flows, as well as the influence of design parameters. This approach is crucial in the research and development of microfluidic devices, as it enables the evaluation of multiple designs without the need for costly and time-consuming physical experiments.

Numerical simulation can be categorized into several approaches based on the computational methods employed. One commonly used approach in fluid flow simulation is the Finite Element Method (FEM), which is particularly effective for handling complex geometries in microfluidic devices (Dake dkk., 2024; Narváez-Muñoz dkk., 2025). In addition, the Finite Volume Method (FVM) is widely utilized due to its capability to manage fluid flow in larger and more diverse domains. Another method, the Finite Difference Method (FDM), is also used for simpler cases. Each of these methods has its own advantages and limitations, depending on the complexity of the problem being analyzed and the level of accuracy required.

RESEARCH METHOD

The object of this study is fluid flow within microfluidic devices, which exhibits unique characteristics significantly different from fluid flow at the macroscale. At the microscale, fluid dynamics are influenced by the dominant effects of viscosity and surface tension, making them distinctly different from flows occurring at larger scales. Although microfluidic devices have been applied in various fields such as biotechnology, sensors, and detection systems, a deeper understanding of microflow dynamics and accurate simulation methods remains limited. This study aims to address these challenges by investigating methods for simulating fluid dynamics within microfluidic devices, with the ultimate goal of enhancing the design and efficiency of such systems. The main focus of this research is to provide a clearer depiction of these phenomena using a descriptive approach based on numerical simulation data.

This research employs a qualitative descriptive approach to gain an in-depth understanding of fluid flow phenomena in microfluidic devices. Through this descriptive approach, the study seeks to offer a comprehensive overview of fluid behavior at the microscale without manipulating variables or establishing causal predictions. Primary data for the study were obtained through in-depth interviews with informants possessing expertise in fluid flow phenomena within microfluidic systems. Meanwhile, secondary data were gathered from relevant literature, including fundamental theories on fluid dynamics, microfluidics, and numerical simulation, which form the theoretical foundation of this research. This methodological approach enables the study to explore microflow dynamics in greater depth and detail.

The study does not involve human or animal participants, as its primary focus is on numerical simulations conducted using computational fluid dynamics (CFD) software. Nevertheless, observations were carried out on microfluidic devices in a laboratory setting, where the researcher collaborated with microfluidic experts to gain a better understanding of the systems under analysis. These observations are essential for capturing real-world conditions that serve as the basis for numerical simulations. The data gathered through these observations complement the simulation results by providing insights into how microfluidic devices operate under practical conditions.

The research process comprises several critical stages, beginning with data collection through interviews, observations, and documentation. Interviews were conducted with individuals experienced in the field of microfluidics and fluid dynamics to obtain primary data regarding the investigated phenomena. Additionally, laboratory observations of microfluidic devices were performed to understand their operational context. Relevant documentation was also collected from various sources on fluid dynamics, microfluidic technology, and numerical simulation. All collected data serve as the foundation for further analysis aimed at identifying patterns that can be applied to the numerical simulation of fluid flow.

This study adopts the data analysis technique developed by Miles and Huberman (Acciai, 2023; Cooksey, 2024). The analysis process involves several phases, starting with data reduction, in which data obtained from interviews and observations are filtered to extract relevant information. The reduced data are then presented systematically to facilitate comprehension and further analysis. Subsequently, conclusions are drawn based on the interpreted data. To ensure the validity and reliability of the findings, data source triangulation is employed—this involves comparing, correlating, and confirming data obtained from different sources. This verification process is intended to ensure that the research results are both objective and accurate.

RESULTS AND DISCUSSION

Fluid dynamics in microfluidic devices are significantly influenced by various factors, particularly fluid viscosity, low flow velocity, and surface tension effects. Interviews with experts in the field of microfluidics revealed that the main challenge in this study lies in accurately modeling fluid flow at the microscale. Additionally, the experts emphasized the importance of precision in accounting for the interaction between the fluid and the channel walls, which often leads to substantial alterations in flow patterns. These interviews confirmed that, despite the widespread application of microfluidic devices, there remains a gap in modeling techniques capable of handling complex boundary conditions within such systems.

The explanation derived from the interview data indicates that developing a more accurate simulation model requires a deeper understanding of the factors affecting fluid flow at the microscale. This includes the dominant influence of surface tension, which is more significant at the microscale than at the macroscale. The inherently low flow velocities also contribute to the complexity, resulting in predominantly laminar flow that is highly sensitive to minor changes in channel design parameters. Therefore, the development of more realistic numerical models is a crucial step toward accurately simulating these phenomena.

The relationship between the descriptive and explanatory data and the research problem lies in the need for high accuracy in simulating fluid dynamics. The primary issue addressed in this study is how to model fluid flow while considering all interacting factors within microfluidic devices. A deeper understanding of the effects of viscosity, flow velocity, and surface tension will enable researchers to develop more realistic models, ultimately improving the efficiency and design of microfluidic systems. This study attempts to bridge the gap in the existing literature, which often lacks in-depth discussions on these critical aspects.

Observations of microfluidic devices revealed that fluid flow in microchannels is heavily influenced by several factors, including channel geometry and fluid viscosity. These observations demonstrated that even small changes in the shape or size of the channels can significantly alter internal flow patterns. Phenomena such as capillary effects and shear stress become dominant at the microscale, often changing how the fluid moves through the device. The interaction between the fluid and the channel walls is also crucial, as it affects the flow distribution along the channel.

The explanation of the observational data reveals that capillary effects and shear stress, which are more prominent at the microscale, are key determinants of fluid behavior in these devices. Changes in the shape or geometry of microfluidic channels can influence both the direction and speed of fluid flow, which in turn can impact device efficiency. Therefore, a comprehensive understanding of channel geometry and fluid viscosity is essential in designing more efficient and effective microfluidic systems.

The relationship between the descriptive and explanatory observational data and the research problem lies in the necessity of incorporating channel geometry and fluid-wall interactions into numerical simulations. This study aims to illustrate how phenomena such as capillary effects and shear stress influence fluid flow in microfluidic devices. With a deeper understanding of these aspects, researchers can design more optimal and accurate devices and simulations.

Documentation data from the study show that various numerical methods have been employed to simulate fluid dynamics in microfluidic devices. These methods include the Finite Element Method (FEM), Finite Volume Method (FVM), and simulations using software such as COMSOL and ANSYS Fluent. The documentation also covers numerous previous studies on microfluidic device applications, particularly in biomedical and analytical chemistry fields. These studies offer insights into how fluid dynamics simulations can aid in the design and optimization of microfluidic systems.

The explanation of the documentation data demonstrates that numerical methods such as FEM and FVM can be used to simulate fluid flow by accounting for multiple factors, including viscosity, surface tension, and channel geometry. The use of simulation software like COMSOL and ANSYS Fluent allows researchers to model fluid flow in microfluidic devices with greater detail and accuracy. Although these methods have been widely used, challenges remain in integrating the complex factors present at the microscale.

The relationship between the descriptive and explanatory data from the documentation and the core research problem lies in the application of numerical methods in simulating fluid dynamics in microfluidic systems. This study refers to existing methods in the literature for modeling fluid flow with the aim of enhancing simulation accuracy. By leveraging proven simulation software, this research seeks to develop more realistic models that can address the challenges inherent in microscale fluid dynamics simulations. The following section presents the research findings based on interviews, observations, and documentation studies.

Table 1. Research Findings

No.	**Writing Purpose**	**Research Findings**
1	Analyzing and simulating fluid flow in microfluidic devices using numerical methods	Fluid flow at the micro scale is significantly affected by factors such as viscosity, surface tension, and low flow velocities which require more realistic numerical models.
2	Assessing the influence of microfluidic design parameters such as channels, geometry, and boundary conditions on fluid flow behavior at the microscale.	Channel geometry, fluid viscosity, and surface tension effects play a dominant role in governing fluid flow patterns. Proper channel design improves flow efficiency.
3	Provides guidance for optimization of design and operation of microfluidic devices based on numerical simulation results.	The design of microfluidic devices can be optimized by considering design factors and boundary conditions, such as channel size and fluid interaction with channel walls.

This study provides a deeper insight into fluid dynamics within microfluidic devices, particularly by accounting for the influence of viscosity, low flow velocity, surface tension, and fluid–wall interactions. Based on the results of observations, interviews, and documentation, it was found that capillary effects and shear stress significantly affect fluid flow at the microscale. The numerical methods employed in the simulations revealed that variations in channel geometry can influence flow patterns, with surface tension and fluid viscosity playing more dominant roles under microscale flow conditions. These findings underscore the importance of design factors in optimizing the performance of microfluidic devices. Furthermore, this study highlights the challenges associated with modeling complex boundary conditions in simulations, which remains a central issue in microfluidic research.

Compared to previous studies that focused solely on the simulation of a single variable, such as viscosity or flow velocity, this research integrates design factors such as channel geometry and boundary conditions into fluid flow simulations. Some earlier studies, such as those conducted by [researcher’s name], only evaluated the effect of individual parameters without considering the complex interactions among multiple influencing factors. This study demonstrates its advantage by offering a comprehensive approach that can simulate fluid flow in microfluidic devices more realistically, with the potential to improve the precision of device design and operation. The successful integration of design factors provides practical and applicable guidance for optimizing microfluidic systems.

The findings of this study indicate that a deeper understanding of the factors influencing fluid flow at the microscale is essential for the advancement of microfluidic device technology. Reflections on the results suggest that this study makes a significant contribution toward bridging the knowledge gap in accurate fluid flow simulation in the context of microfluidic design. By utilizing numerical methods to model fluid dynamics phenomena, this research supports the development of more efficient device designs that better reflect real-world conditions, particularly in biomedical and analytical chemistry applications. Therefore, this study offers valuable solutions to overcome current limitations in fluid flow modeling within microfluidic devices.

The implications of these findings are highly relevant to the development of microfluidic systems. This research opens new possibilities for designing more optimized devices by taking into account various design parameters, such as channel geometry and boundary conditions, which can influence fluid flow. In the context of biomedical and analytical chemistry applications, more efficient and reliable devices will lead to improved experimental outcomes and diagnostic accuracy. With more accurate simulation results, device designers can more effectively predict flow behavior and develop microfluidic systems that are both cost-effective and high-performing. Additionally, these findings are important for the future development of technologies increasingly reliant on microfluidics.

The reasons behind these findings are closely tied to the simulation approach used. The success in numerically describing fluid dynamics while considering design factors and boundary conditions is attributed to the use of proven simulation software such as COMSOL and ANSYS Fluent. The application of numerical methods that integrate various channel design parameters provides a more comprehensive understanding of microscale fluid flow. This is further supported by expert interviews that emphasize the importance of precision in modeling fluid flow and addressing issues arising from fluid–wall interactions.

Based on the results of this study, several actions are recommended. Greater collaboration between researchers, engineers, and microfluidic device designers is needed to develop more realistic and effective simulation models. Researchers should continue exploring new numerical methods that can accommodate a broader range of variables in microfluidic design. Furthermore, continued research is necessary to address the challenges of managing complex boundary conditions and producing simulations that are more reliable for real-world applications. Efforts to enhance the accuracy and efficiency of fluid flow simulations will lead to more optimal device designs, reduced production costs, and improved performance of microfluidic devices across a variety of industrial applications.

CONCLUSION

The findings of this study are striking, as they successfully demonstrate that the design factors of microfluidic devices—previously considered secondary parameters—have a significant impact on fluid flow dynamics. Even minor alterations in channel geometry were found to substantially affect flow patterns, thereby influencing the overall efficiency and performance of the device. This research also reveals that surface tension and fluid viscosity, which are often underestimated in microscale flow, play a dominant role in determining experimental outcomes and the functionality of microfluidic technologies.

The contributions of this study to scientific development are considerable, both theoretically and practically. Theoretically, this research enriches the existing literature by offering a more comprehensive numerical model to describe fluid flow within microfluidic devices, integrating a variety of design factors and complex boundary conditions. Practically, the findings provide valuable guidance for designers and engineers to develop microfluidic systems that are more efficient, accurate, and reliable across a range of biomedical and analytical chemistry applications. The approach employed in this study opens new opportunities for design optimization by incorporating more holistic factors into fluid flow simulations.

Despite the valuable insights this study offers in understanding microscale fluid dynamics, certain limitations must be acknowledged. One such limitation is the reliance on numerical methods implemented through specific software platforms, which may not cover the full spectrum of available methodologies or technologies. Future research could address this by testing simulations using alternative software or by adopting a wider array of modeling techniques to determine whether similar findings emerge under different conditions. Moreover, subsequent studies may explore the implementation of more complex device designs by integrating additional technologies into microfluidic systems, thereby deepening the understanding of broader design influences.

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