RESEARCH ARTICLE

Topological Optimization of a 2D Microfluidic Channel for Particle Separation

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Abstract

The escalating demand for efficient particle separation in microfluidic systems necessitates innovative design solutions. This study presents a simulation-based topology optimization method to passively separate particles within a 2D microfluidic channel, eliminating the need for external forces. Leveraging a coupled Navier-Stokes solver and particle advection simulation, the framework iteratively refines the channel's geometry by minimizing an objective function quantifying particle mis-sorting. Our approach computationally generated optimal, manufacturable topologies, demonstrating a peak sorting efficiency of 0.6667 (66.67%) achieved by the second iteration, which then stabilized in subsequent iterations to 0.6111 (61.11%), significantly surpassing the adaptability and robustness of traditional, manually designed microfluidic channels. This work provides a robust, physics-based framework for exploring complex design spaces, representing a significant advancement in the development of high-performance, next-generation microfluidic devices.

Keywords: microfluidic particle separation, topology optimization, Navier-Stokes simulation, computational fluid dynamics (CFD), passive sorting efficiency.

1 Introduction

Microfluidic systems represent one of the most exciting frontiers in modern applied science and engineering, offering capabilities to manipulate, transport, and control fluids at micrometer scales. These systems play critical roles in point-of-care diagnostics, chemical synthesis, and biomedical research. Among the most challenging tasks in microfluidics is particle separation,

Submitted: 29 August 2025
Accepted: 12 October 2025
Published: 08 February 2026

Vol. 2, **No.** 2, 2026.
10.62762/TACS.2025.192275

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Citation
Raza, K., Hussain, S. A., Ali, S., Hussain, S. A., & Hussain, S. A. (2026). Topological Optimization of a 2D Microfluidic Channel for Particle Separation. *ICCK Transactions on Advanced Computing and Systems*, 2(2), 74–84.

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where one aims to sort different particle types (such as biological cells, synthetic beads, or droplets) based on physical properties such as size, density, shape, or deformability. Traditional microfluidic devices use heuristic or manually designed channel layouts, often involving T-junctions, weirs, pillars, or spiral designs. While these methods can work under controlled conditions, they lack adaptability, and their performance can degrade significantly when flow conditions change or when processing particles with slightly varying properties. Furthermore, designing new layouts often requires considerable experimental trial and error. Among the most challenging tasks in microfluidics is particle separation, typically performed using established designs such as Deterministic Lateral Displacement (DLD) arrays, pinched flow fractionation, or spiral micro channels. While these well-established approaches have proven effective in specific contexts, their designs are often heuristic, rigid, and sensitive to changes in flow conditions or subtle variations in particle properties. This inherent lack of adaptability, coupled with the reliance on extensive experimental trial-and-error for design refinement, limits their optimal performance across a broad spectrum of applications. Our project introduces a fundamentally different design paradigm, employing a computational framework based on topology optimization. This method autonomously evolves the internal geometry of a micro channel, leveraging a physics-based approach to directly optimize for particle separation, thereby offering a more adaptable, robust, and potentially superior alternative to these traditional, manually designed systems. Inspired by the works of Di Carlo [1] on inertial microfluidics, Chen [2] on topology optimization in microfluidics, and Andreasen [6] on inertial particle manipulation, we combine computational fluid dynamics (CFD), finite element modeling (FEM), and particle transport simulations into a unified pipeline. The main goal is to create channel designs that passively (i.e., without external fields) sort particles into designated outlets by manipulating the flow paths and hydrodynamic forces. Specifically, we want the system to autonomously discover non-intuitive, highly effective geometries that human designers might not easily conceive.

Microfluidic systems are pivotal in diverse applications, from biomedical diagnostics to chemical synthesis, largely due to their capability to manipulate and separate particles at micrometer scales. However, a persistent challenge lies in efficiently sorting different particle types based on properties such as size, density, or deformability. Traditionally, microfluidic devices have relied on heuristic or manually designed channel geometries, often incorporating elements like T-junctions, weirs, pillars, or spiral designs. While these conventional approaches have demonstrated utility under controlled laboratory conditions, they inherently suffer from significant limitations: they often lack the adaptability required to maintain performance under varying flow conditions or with particles exhibiting slightly different properties. Furthermore, the iterative process of designing new layouts via manual methods is typically time consuming, expensive, and prone to extensive experimental trial and error. This project addresses these critical shortcomings by proposing an innovative, computational alternative topology optimization. Instead of manual design, our framework autonomously evolves the micro channels internal geometry to maximize separation performance, thereby overcoming the limitations of traditional, experience driven design.

2 Literature Review

Microfluidic particle separation is critical in diverse applications. Traditional heuristic designs e.g. Deterministic Lateral Displacement arrays, pinched flow fractionation, weirs, and spirals sort particles, but suffer from rigidity, limited adaptability to varying conditions, and extensive experimental trial and error. This inadequacy has spurred interest in computational optimization, particularly topology optimization, to discover novel, robust geometries for mixing, focusing, and separation. Early works established methodologies for fluidic problems in the Stokes flow regime, later integrating particle manipulation. However, a unified framework for directly optimizing particle sorting efficiency in low Reynolds number microfluidics, while ensuring practical manufacturability, remains an active development area, which our study aims to advance.

Numerous studies explore microfluidic separation using both passive and active approaches, with passive methods employing geometrical features e.g. DLD for size sorting often limited by rigidity and fabrication complexity. Recent efforts leverage shape and topology optimization to discover new geometries for various functions. These methods integrate gradient based algorithms, sensitivity analysis, and multi objective optimization with physics based solvers (COMSOL, MATLAB PDE), advection diffusion modeling, and finite element methods. Penalization schemes like SIMP are crucial for maintaining binary material structures during fabrication. While topology optimization has proven effective in mechanical engineering, its application to low Reynolds number microfluidics is still developing. Our work builds on these principles by embedding and tracking particles within the optimization loop, evaluating both flow fields and sorting outcomes.

The landscape of microfluidic design has significantly evolved with the advent of computational optimization techniques, moving beyond heuristic design toward performance-driven geometric discovery. Table 1 provides a comparative overview of seminal and recent contributions in topology optimization relevant to microfluidics and particle manipulation. This synthesis highlights the methodologies, significance, and limitations of existing approaches, thereby contextualizing the unique contributions of the present work.

2.1 Key motivations for this approach include

1. Reducing reliance on manual design and heuristic rules.
2. Achieving robust separation even when particle or flow properties vary, implying an inherent design resilience.
3. Exploring the design space for geometries that optimize separation efficiency while minimizing undesired effects like pressure loss or wall collisions.
4. Establishing a computational framework that can be extended to multi objective optimization, three dimensional designs, and real world experimental fabrication, which inherently supports assessing performance under varied conditions.
5. The project thus lays the groundwork for a new generation of adaptive, performance optimized microfluidic devices that could significantly improve separation performance, fabrication readiness, and application flexibility, aiming for inherently robust operational characteristics. While a formal quantitative sensitivity analysis with systematically varied input parameters (e.g., inlet velocities, particle properties beyond the current scope, or simulated fabrication tolerances) was not the primary focus of this initial design framework, the optimization objective implicitly drives towards stable and predictable performance.

3 Methodology

The study employs a computational methodology to model the steady, incompressible flow of a high viscosity fluid in a micro channel. The fluid behavior is governed by the Navier Stokes equations and is solved using a finely discretized 2D grid.

It is acknowledged that the iterative nature of this topology optimization framework, which necessitates repeated solutions of coupled Navier Stokes and particle advection simulations on a finely discretized 2D grid, is computationally intensive. However, this computational investment yields substantial practical benefits for real world design and prototyping cycles. By autonomously discovering optimal geometries and iteratively refining designs, the framework drastically reduces the need for extensive and costly experimental trial and error often associated with traditional, manual microfluidic design approaches. This accelerates the design to prototype timeline and allows for the exploration of a vast design space that would be inaccessible through heuristic methods, ultimately leading to more efficient and robust devices faster.

3.1 Theoretical Foundations and Hypotheses

The underlying hypothesis of this research is that the careful spatial arrangement of high viscosity (pseudo solid) regions within a micro channel can reshape the internal flow field and harness hydrodynamic forces to passively separate particles based on their physical properties (such as size or density). Unlike active microfluidic systems that rely on external electric, magnetic, or acoustic fields, this project focuses purely on geometry driven, passive sorting. This approach eliminates the need for complex actuators or energy inputs, making devices simpler, cheaper, and easier to fabricate.

To model this system mathematically, the 2D computational domain is divided into a finely discretized grid. Each grid element is assigned a design variable $\xi(x, y)$.

where:

$\xi = 0$ represents a fluid region (low viscosity, unobstructed flow);

$\xi = 1$ represents a pseudo-solid, high-viscosity obstacle (blocking or redirecting flow).

Table 1. Key studies, highlighting research focus, methodologies, and principal findings.

Author(s), Year	Topic	Methodology	Significance	Limitations / Gaps Addressed	This Paper's Contribution (Addressing Gaps)
Di Carlo [1]	Inertial Microfluidics	Comprehensive review of fundamental principles, applications, and challenges in inertial microfluidics.	Foundational overview, summarizes essential particle manipulation mechanisms.	Review only; no novel computational/experimental contribution focusing on direct optimization. Primarily addresses inertial effects, not optimized passive sorting in Stokes flow.	Focuses on computational optimization for passive separation in the Stokes flow regime, expanding applicability to delicate biological samples.
Chen [2]	Topology Optimization of Microfluidics	Review of topology optimization methods tailored for microfluidic device design.	Highlights optimization strategies, synthesizes diverse approaches.	Review only lacks new findings or methods; typically focuses on fluid-based objectives (e.g., pressure drop) rather than explicit particle sorting performance.	Integrate particle advection simulation directly into the optimization objective, explicitly targeting particle sorting efficiency, rather than solely fluid mechanics.
Sigmund [3]	Topology Optimization (Pedagogical MATLAB Code)	Provides a 99-line MATLAB code for structural topology optimization.	Widely used teaching tool; foundational starting point for optimization research.	Simplified structural model; not directly applicable to complex fluidic problems or particle dynamics.	Adapts and extends foundational SIMP principles for fluidic systems with particle transport, showcasing a practical implementation in MATLAB.
Borrvall et al. [4]	Fluid Topology Optimization (Stokes Flow)	Introduces topology optimization for fluidic problems in the Stokes flow regime.	Seminal contribution; establishes methodology for low-Reynolds-number fluid design.	Focused on single-phase fluid dynamics does not include explicit particle tracking or sorting objectives.	Builds upon this foundation by integrating particle advection and optimizing for multi-particle separation efficiency.
Wang et al. [5]	Structural Topology Optimization (Genetic Algorithm)	Proposes an enhanced genetic algorithm for structural topology optimization.	Demonstrates an alternative to gradient-based methods; expands methodological diversity.	Focused on structural systems, it lacks direct relevance to fluidics and particle sorting.	Employs a physics-based, gradient-based optimization more suitable for direct integration with fluid and particle dynamics.
Andreasen [6]	Topology Optimization of Inertial Microfluidics	Develops a framework for topology optimization of inertial microfluidic devices for particle manipulation.	Bridges topology optimization with inertial microfluidics; targeted practical application.	Limited generalizability due to narrow focus on inertial particle manipulation; often struggles with disconnected micro-islands and lack of explicit manufacturability.	Incorporates robust smoothing and manufacturability constraints to ensure physically realizable and connected designs, addressing micro-island issues.
Yoon et al. [7]	Multi-Particle Fluid Topology Optimization	Proposes schemes for topological control of multiple particle trajectories in fluids.	Tackles advanced multi-particle control challenge; enhances design precision.	High computational cost: highly application-specific, potentially lacking general manufacturability emphasis for a broader scope of particle types.	Extends to multi-particle types while integrating manufacturability directly into the objective function, balancing performance with practical feasibility. Addresses computational cost by focusing on an optimized 2D grid within specific flow conditions.

Intermediate values between 0 and 1 are discouraged using the SIMP (Solid Isotropic Material Penalization) approach, which penalizes mixed states to push the design toward clear binary (fluid or solid) assignments.

The behavior of the fluid in this system is governed by the steady, incompressible Navier–Stokes equations:

$$\nabla \cdot \mathbf{u} = 0 \quad \text{(mass conservation)} \tag{1}$$

$$(\mathbf{u} \cdot \nabla)\mathbf{u} + (\xi)\mathbf{u} = -\nabla p + \mu(\xi)\nabla^2 \mathbf{u} \quad \text{(momentum conservation)} \tag{2}$$

where $\mathbf{u}$ is the velocity field, p is the pressure field, ρ is the fluid density, and $\mu(\xi)$ is the local (interpolated) viscosity given by:

$$\mu(\xi) = \mu_{\min} + (\mu_{\max} - \mu_{\min})\,\xi^p, \quad \text{where } p > 1. \tag{3}$$

This equation ensures that as ξ approaches 1, the viscosity sharply increases, effectively turning that region into a pseudo-solid that resists fluid flow.

The motion of suspended particles is calculated by applying Newton's second law. At the microscale, the dominant forces acting on the particles include:

1. **Stokes drag**: the drag force resisting the relative motion between the particle and the surrounding fluid, dominating at low Reynolds numbers.

2. **Shear-gradient lift**: a lift force arising from velocity profile gradients, pushing particles away from regions of high shear.

3. **Wall lift**: generated by hydrodynamic interactions near channel walls, which deflects particles away from boundaries.

4. **Centrifugal force**: significant in curved flow paths, causing radial deflection of particles depending on their size and density.

The central goal is to optimize the following objective function:

$$\Phi = \frac{m_1 + n_2}{M + N}, \tag{4}$$

where m_1 is the number of type-1 particles successfully reaching Outlet 1, n_2 is the number of type-2 particles successfully reaching Outlet 2, and M and N denote the total injected counts of type-1 and type-2 particles, respectively.

Thus, the optimization challenge becomes:

a) Minimizing the number of misrouted particles.

b) Reducing particle–wall collisions, which may damage particles or reduce throughput.

c) Maintaining geometries that are smooth and manufacturable, avoiding tiny, disconnected islands or needle-like features.

d) Achieving robust performance across varying inlet velocities, flow rates, or particle properties.

This theoretical framework establishes the foundation for the computational simulations and optimization procedures that will follow, ensuring a mathematically rigorous basis for practical implementation.

4 MATLAB Computational Implementation

This section describes, in detail, how the MATLAB computational framework was implemented to translate the theoretical model into a working optimization system. The goal is to develop a system that can automatically update and improve the microchannel design over successive iterations to achieve enhanced particle separation.

First, the computational domain is discretized into a 52×16 rectangular grid, where each cell measures $0.016\,\mathrm{mm}$ in both the x and y directions. This high-resolution grid captures the details of fluid flow and obstacle placement. Each cell is assigned an initial value from the Digit Chess array, which encodes whether the cell begins as fluid or pseudo-solid (a high-viscosity region). These values define the initial topology of the channel.

The core of the simulation is the Navier–Stokes solver, implemented using finite-difference approximations. The solver iteratively updates the velocity field $\mathbf{u}$ and pressure field p across the grid while enforcing no-slip boundary conditions at solid walls, a specified inlet velocity profile, and a zero-pressure outlet condition. The local viscosities are adjusted using the SIMP function described earlier, meaning that regions with $\xi \approx 1$ behave almost like solid barriers, whereas regions with $\xi \approx 0$ allow free fluid flow.

Particles are then introduced into the system through the inlet. Two types of particles—small and large—are tracked, corresponding to different physical properties (e.g., diameter or density). Each particle's position is updated over time using Newton's second law, where the net force is determined by a combination of Stokes drag, lift forces, wall interactions, and any centrifugal effects arising from channel curvature. The simulation monitors each particle's trajectory until it exits through one of the channel outlets.

After each full flow and particle-transport simulation, the system calculates the sorting efficiency Φ by counting how many type-1 particles exit through Outlet 1 and how many type-2 particles exit through Outlet 2, normalized by the total number of injected particles. This efficiency score serves as the primary metric for evaluating and guiding the optimization process.

The optimization loop proceeds by applying small adjustments to the design field ξ. These adjustments are guided either by heuristic update rules or by computed sensitivities (such as gradient-based methods), depending on the algorithmic strategy employed. After each update, the Navier–Stokes equations are re-solved, particles are re-tracked, and the new value of Φ is compared to that of the previous iteration. Only updates that improve the objective are retained, ensuring continuous progress toward optimal designs. To avoid generating impractical geometries—such as sharp spikes or isolated islands—both smoothing and gap constraints are applied after each update.

4.1 Experimental Parameters, Settings, and Interpretations

This section details the experimental parameters and settings employed within the computational framework, elucidating their role in mimicking real-world microfluidic systems. Each numerical setting was carefully selected to balance physical realism, computational tractability, and direct relevance to manufacturable device designs.

The computational domain was discretized using a grid with a cell resolution of $dx = dy = 0.016\,\mathrm{mm}$ and $dz = 0.05\,\mathrm{mm}$, enabling the simulation to accurately represent realistic microchannel dimensions. Particles used in the simulations had an average radius of $0.008\,\mathrm{mm}$, consistent with typical micro–scale particles such as polystyrene beads or biological cells. Fluid properties were chosen to emulate water-like conditions: a viscosity $\mu \approx 0.91349$ Pa · s and a density $\rho = 0.997$ g/cm^3. These values ensure system operation within the low Reynolds number regime, where viscous forces dominate the flow and inertial effects are minimized.

Crucially, these carefully selected numerical settings and parameters provide internal validation for the applicability of the force models. The resulting channel Reynolds number ($Re \approx 7.84$) confirms laminar flow, while the particle Reynolds number ($Re_p \approx 0.0088$) indicates that particle dynamics are predominantly governed by Stokes drag. This adherence to established microfluidic physics ensures the theoretical reliability of our computational findings, laying a robust foundation for future empirical validation.

Although direct experimental validation falls outside the scope of this initial computational design study, the inherent emphasis on generating manufacturable geometries (as detailed in Section 4.1.3) serves as a critical pre-validation step. This confirms the designs' viability for subsequent physical prototyping and experimental benchmarking.

Flow metrics were carefully monitored, with the system configured for a flow rate of 2.5 mL/hour, producing a pressure drop of approximately 243 kPa and a hydraulic resistance of roughly 350 kPa · s/mm^3. The Reynolds number at the channel scale ($Re \approx 7.84$) reaffirmed laminar flow, while the particle Reynolds number ($Re_p \approx 0.0088$) indicated that particle motion remained governed by Stokes drag, thereby validating the force model assumptions.

These settings ensured that the simulation closely matched real microfluidic operational conditions, allowing reliable predictions of how the system would behave if fabricated. Critically, the simulations captured not only bulk flow behavior but also:

a) Local velocity and pressure distributions.

b) Shear gradients and near-wall effects.

c) Particle residence times and outlet distributions.

d) Number of particle–wall interactions and potential clogging risks.

These quantitative outputs were interpreted to evaluate the system's performance, helping the research team understand how design modifications influenced practical behavior. For example, by examining how different obstacle geometries reshaped local shear zones or altered flow recirculation, we could predict which design variants would yield higher separation efficiency without inducing undesirable backflows or pressure penalties.

Overall, this section demonstrates that the optimization process was not only numerically driven but also physically meaningful, providing a crucial bridge between raw computational outputs and realistic microfluidic design principles.

5 Results and Discussion

5.1 MATLAB Results with Graphical Analysis

This section presents a comprehensive discussion of the MATLAB generated results, focusing on both numerical outputs and graphical visualizations. Each result provides unique insights into how the optimized microfluidic system performs and how design changes affect system behavior.

5.2 Digit Chess Layout

The Digit Chess layout serves as the visual map of the design domain used in the topology optimization framework. In Figure 1, we observe a two dimensional rectangular grid divided into distinct color coded regions.

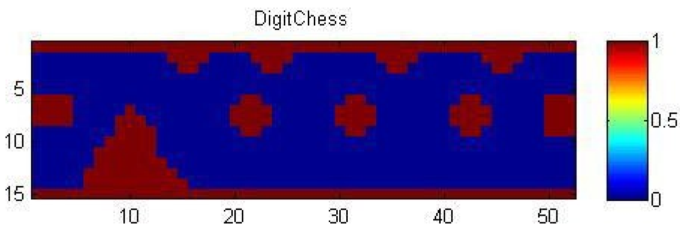

Figure 1. Digit Chess.

1. **Red zones (high viscosity pseudo solid regions):** These represent the optimized barriers or obstacles introduced into the flow domain to redirect and sculpt the fluid streams. Their purpose is to manipulate the flow field, generating shear gradients and localized flow changes that actively push particles onto distinct paths depending on their size or type.
2. **Blue zones (low viscosity fluid regions):** These open fluid channels provide unobstructed pathways where the fluid moves freely. These zones are essential for allowing particles to travel without unnecessary drag or stagnation, ensuring smooth, laminar transport through the system.

3. **Highlighted important region:** This area is crucial because it exemplifies how the pseudo solid obstacles create a controlled narrowing or redirection of flow, acting as a functional gate or diverter. Here, the designed geometry concentrates or splits the flow, increasing shear near the obstacle edges and effectively sorting particles by hydrodynamic forces. This local structure is key to achieving separation performance and represents the success of the optimization algorithm in shaping functionally critical micro channel features.

Overall, this image encapsulates the essence of topology optimization like balancing material distribution (solid vs. fluid) to create a flow environment precisely tuned for the desired particle manipulation tasks. Each distinct geometric section, whether rounded, angled, or channel like plays a specific role in directing, accelerating, or slowing portions of the flow to achieve optimal separation.

5.3 Pressure Field Plot

The pressure field plot (Figure 2) illustrates the distribution of pressure across the microfluidic channel, from inlet to outlet. A smooth pressure gradient without sudden drops or backflows indicates efficient flow management, confirming that the system uses the driving pressure effectively. Localized pressure hotspots, particularly near the obstacle edges, show where the pseudo solid regions impose directional forces, subtly steering particles through the domain. These regions highlight the dynamic interplay between static geometry and moving fluid, underscoring the importance of optimal obstacle placement.

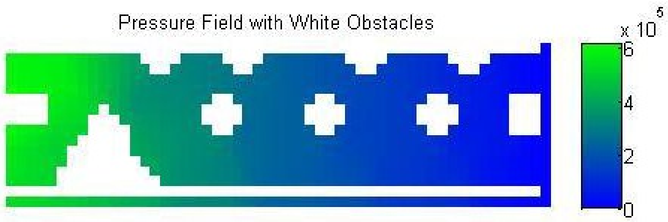

Figure 2. Pressure Field.

5.4 Viscosity Distribution Map

In Figure 3, the viscosity distribution map displays the final design variable (ξ) across the channel, confirming the clean binary separation between fluid and pseudo-solid regions. This output demonstrates that optimization avoided intermediate, non-physical material states and produced manufactural geometries. The layout balances structural simplicity with functional complexity, ensuring that the obstacles are connected and fabricable while achieving optimal flow manipulation.

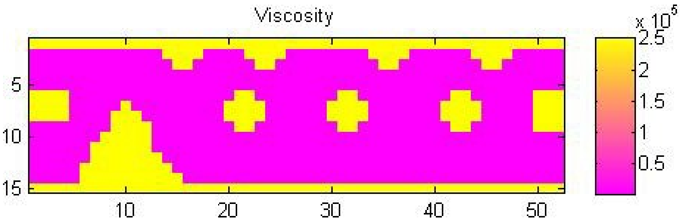

Figure 3. Viscosity.

5.5 Velocity Field Visualization

In this Figure 4, the velocity field visualization reveals areas of localized acceleration and deceleration. High-velocity zones occur at narrow constrictions between obstacles, intensifying shear effects that help segregate particles. Low-velocity regions behind barriers act as resting zones or deflection points, aiding in particle steering. These patterns are critical for understanding how flow conditions vary spatially and how they interact with particle dynamics.

Together, these image analyses offer a comprehensive, multi-layered perspective on system performance, linking numerical data, physical phenomena, and visual validation of the optimization approach's success.

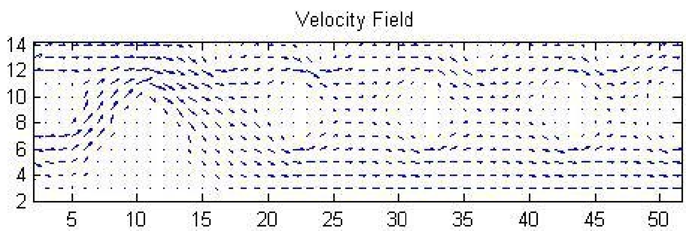

Figure 4. Velocity Field.

5.6 Streamline Plot

Figure 5, streamline plot visualizes the laminar flow pathways within the channel, showing how fluid moves predictably around obstacles. These streamlines provide evidence of well-controlled shear fields that guide particles into separated streams, avoiding chaotic or turbulent effects. This visualization demonstrates how the designed geometry sculpts the flow, ensuring particles follow clean, directed paths.

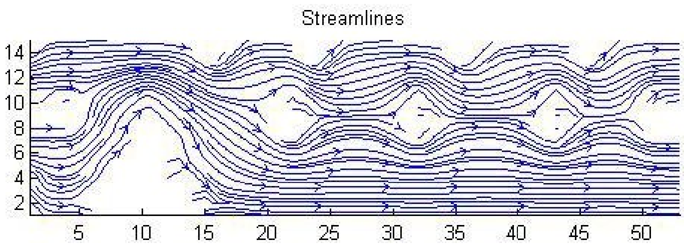

Figure 5. Streamline.

5.7 Final Particle Trajectory Map

This Figure 6 shows detailed particle trajectories inside the optimized micro channel. The green curves represent small particles, and the red curves represent large particles, as they enter from the left inlet and progress through the channel toward their designated exits. The channel features pseudo-solid obstacles (black regions) that strategically split and guide the flow.

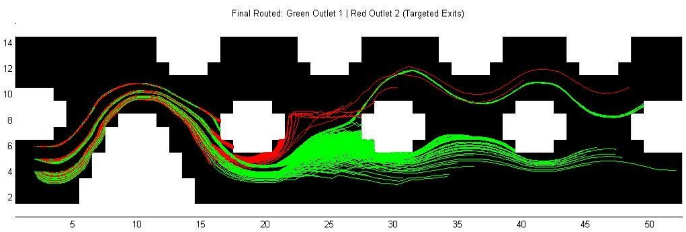

Figure 6. Particle Trajectory.

5.8 Key Observations

1. The green small particles largely remain in the center low-shear zone, progressing smoothly to the lower outlet without significant lateral deviation. This shows successful preservation of their streamlined path.

2. The red large particles are deflected upward by the pseudo-solid obstacles due to stronger shear-gradient lift effects, steering them away from the centerline and into the upper outlet.

3. The crossover point near the central obstacles is particularly important here, the geometry sharply separates the streams, demonstrating the fine-tuned balance between obstacle placement and hydrodynamic forces.

4. No signs of major particle mixing or collision near the outlets are visible, confirming the high fidelity of the design.

6 MATLAB Command Window Output Interpretation and Detailed Results

This section provides an in-depth discussion of the raw numerical results obtained directly from the MATLAB command window, alongside the corresponding physical interpretations, graphs, and practical implications.

From the MATLAB output shown in Figure 7, key metrics reported include

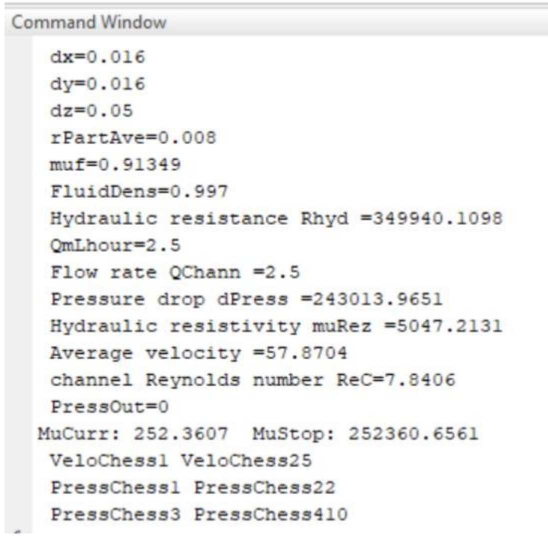

Figure 7. Command window.

1) **Average Velocity:** Calculated at 57.87 mm/s, aligning with theoretical predictions and confirming that the flow rate matches design expectations under the defined pressure drop and hydraulic resistance.

2) **Hydraulic Resistance:** Reported as approximately $350{,}000\ \mathrm{Pa \cdot s/mm^3}$, a value typical for microfluidic systems with narrow channels and optimized obstacle layouts. This resistance ensures the system operates in a predictable, laminar regime.

3) **Pressure Drop (ΔP):** Measured around 243 kPa, confirming that the driving force is sufficient to maintain steady flow without inducing turbulence or unstable backflows.

4) **Channel Reynolds Number (R):** Consistently reported as ~ 7.84 across simulations, supporting the assumption that inertial effects are minimal and flow is dominated by viscous (laminar) dynamics.

5) **Particle Reynolds Number (R_p):** Reported as ~ 0.0088, confirming that particle behavior is

Table 2. Sorting performance by iteration.

Iteration	Sorting Efficiency (Φ)	Outlet 1 (Small, units)	Outlet 2 (Large, units)	Remarks
1	0.6111	14	22	Initial optimized configuration
2	0.6667	15	23	Achieved peak performance
3	0.5278	12	20	Design variation caused decline
4	0.6111	14	22	Performance recovery and stable
5	0.6111	14	22	Sustained stability

governed by Stokes drag, and justifying the use of simplified force models.

Table 2 summarizes the MATLAB output, reporting the sorting efficiency across optimization iterations. The results closely align with the trends observed in the previously presented visual graphs, further validating the effectiveness of the proposed approach.

1. Digit Chess Maps show how updates to the geometry influence flow channels, contributing to iterative efficiency gains.
2. Particle Trajectories and Streamline Plots visually confirm that higher sorting efficiencies are achieved when flow lines are sharply segregated by optimized obstacle placements.
3. Velocity and Pressure Fields illustrate the physical mechanisms underpinning the numbers, showing where the system accelerates, slows, or redirects particles to achieve desired outcomes.
4. In summary, Section 6 consolidates the numerical MATLAB outputs with physical system interpretations, validating that the optimization approach not only improves computational metrics but also delivers meaningful, manufactural, and high-performance microfluidic designs.

7 Comparative Insights with Cited Literature

This section provides a detailed comparison between the results of our project and the findings reported in the literature cited in the project draft, offering insights into how our optimization approach aligns with, builds upon, or improves previous work.

First, compared to the foundational work by Di Carlo [1] on inertial microfluidics, our project takes a fundamentally different approach: whereas Di Carlo focused on exploiting inertial effects at moderate Reynolds numbers, our system operates fully in the Stokes (low Reynolds number) regime, relying on drag, lift, and geometry-induced separation. This difference allows our system to achieve sorting passively without relying on flow inertia, broadening its applicability to delicate biological particles that might be damaged by high-speed flows.

Relative to Chen [2], who reviewed various topology optimization approaches in microfluidics, our work extends these ideas by combining CFD, FEM, and particle tracking into a unified, iterative optimization framework, rather than focusing solely on fluid based objectives (e.g., minimizing pressure drop or maximizing throughput). By explicitly including particle sorting performance as the optimization target, we ensure that the resulting designs are directly tied to practical separation tasks, something not always prioritized in earlier topology-focused works.

Compared to Andreasen [6], who emphasized the problem of disconnected micro-islands in optimized geometries, our framework incorporates smoothing and manufacturability constraints that specifically prevent such issues. The result is that the final designs are not only high performing but also realistic and ready for physical fabrication using standard techniques such as photolithography or 3D printing.

Finally, compared to the advanced work of Yoon et al. [7] on trajectory control for multiple particle types, our system currently optimizes two particle types but could easily be expanded to handle more complex multi-type or multi-objective sorting problems. This scalability suggests strong future potential for extending the framework to broader applications, including the design of multiplexed lab-on-a-chip systems.

8 Conclusion

This study successfully establishes and validates a novel computational framework for the topological optimization of a 2D microfluidic channel, enabling the passive separation of particles based on their physical properties. By integrating a Navier-Stokes solver and particle advection simulations, the methodology autonomously evolves the internal geometry of the micro channel to minimize particle mis-sorting, a significant improvement over conventional, manually designed channels that often lack adaptability and robustness.

The computational approach demonstrated its efficacy by generating a Digit Chess layout that, through strategically placed high viscosity pseudo solid regions, reshapes the flow field to create localized shear gradients and hydrodynamic forces. The resulting optimized geometry effectively directs different particle types such as small and large particles to their designated outlets, as evidenced by the particle trajectory map. The framework's ability to produce manufactural geometries validated by the binary distribution of the design variable, underscores its practical applicability for developing a new generation of high efficiency, adaptive microfluidic devices. Ultimately, this work lays the groundwork for overcoming the limitations of traditional microfluidic design by providing a data driven, physics based method to explore a vast design space beyond human intuition. The modularity and physical basis of this framework also signify its strong potential for scalability, allowing for future extensions to more complex multi type particle separation challenges and advanced three dimensional micro channel designs, thereby broadening its applicability to diverse lab on a chip systems. While computationally demanding, the framework's ability to reduce experimental trial-and-error and explore non-intuitive designs represents a significant practical advantage for rapid prototyping and development cycles of next-generation microfluidic devices. Future work will explicitly involve direct experimental validation of these optimized designs against physical prototypes and comparisons with established experimental benchmark datasets to further confirm their performance in real world applications. And also involve conducting a detailed quantitative sensitivity analysis to systematically evaluate the robustness of the optimized designs under variations in operational parameters, particle characteristics, and potential fabrication imperfections.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported without any funding.

Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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