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Qi Wang  ; Yuan-Qing Xu  

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Qi Wang  and Yuan-Qing Xu^{a)} 

AFFILIATIONS

School of Medical Technology, Beijing Institute of Technology, Beijing, China

^{a)} Author to whom correspondence should be addressed: bitxyq@bit.edu.cn

ABSTRACT

This study investigates the inertial focusing behavior of curved filaments in straight microchannels to elucidate the individual effects of filament length, curvature, elasticity, and the channel Reynolds number (Re). Numerical simulations were performed using the immersed boundary-lattice Boltzmann method. The validity of the model was confirmed through grid independence tests and by comparing simulated inertial focusing of rigid particles with existing experimental benchmarks. Increasing filament length shifts the equilibrium position toward the channel centerline, broadens the focusing distribution, and prolongs the rotational period. Conversely, highly curved filaments focus farther from the centerline, exhibit a tighter focusing band, and rotate faster. Elasticity exerts a relatively minor influence, resulting only in a slight outward shift and marginal changes in the rotation period. Furthermore, higher Reynolds numbers—associated with steeper velocity gradients—drive focusing positions outward and compress the focusing interval, while simultaneously extending the rotational period. The inertial focusing of curved filaments is governed by the interplay of geometric configuration, mechanical properties, and flow conditions. These findings provide a theoretical basis for manipulating and separating curved particles in microfluidic systems.

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I. INTRODUCTION

Inertial focusing is a fluid–structure interaction phenomenon wherein suspended particles laterally migrate to specific equilibrium positions within a channel cross section. This effect was first experimentally documented by Segre and Silberberg¹ in 1961, who observed that 1 mm-diameter particles in a 10 mm circular tube formed an annular band at a radial position of ~ 0.6 times the tube radius—a phenomenon later termed the “tubular pinch effect.” They attributed this migration to inertial effects in Poiseuille flow, distinct from the Stokes flow regime, where viscous forces and flow symmetry prevent particles from crossing streamlines. The underlying mechanism, elucidated by Asmolov and Manuilovich,² stems from the inertial terms in the Navier–Stokes equations. Mechanical equilibrium is achieved through a balance between two hydrodynamic lift forces: a shear-gradient lift force, directed toward the channel wall due to the curvature of the velocity profile, and a wall-induced lift force, which pushes the particle away from the wall toward the channel center. The interplay between these inertial and viscous effects dictates the final stable focusing positions.³ This principle was successfully adapted to microfluidic systems by Di Carlo

*et al.*⁴ in 2007. Their study demonstrated that particles ranging from 2 to 17 μm in diameter could predictably focus in microchannels with widths of 10–87 μm without external forces. By exploiting geometry-induced variations in equilibrium positions, this breakthrough established inertial microfluidics as a high-throughput method for label-free particle separation.

Recent years have seen extensive global investigation into particle inertial focusing, revealing substantial potential in biological separation and medical diagnostics. Ali *et al.*⁵ demonstrated that the distinct inertial focusing positions of larger circulating tumor cells (CTCs) compared to smaller erythrocytes allow for their effective isolation from whole blood. Capitalizing on these dimensional disparities, Xu *et al.*⁶ optimized the cross-sectional geometry and flow parameters of multi-stage microchannels, achieving 98.1% purity in CTC separation. This study was further advanced by Sun *et al.*⁷ who refined the arc structural parameters of microchannels to attain 99.8% purity, thereby facilitating the translation of inertial focusing into precision clinical testing. In the context of pathogen detection, Ardila *et al.*⁸ developed a rapid microfluidic chip for *Staphylococcus aureus* that reduced assay time and reagent consumption while supporting clinical antibiotic selection.

Similarly, Rosenbach *et al.*⁹ employed inertial microfluidics to capture *T*-lymphocytes from whole blood for RNA analysis, enabling physiological monitoring of severe burn patients and providing data to support emerging immune-targeted therapies. In industrial microbial sorting, Liu *et al.*¹⁰ exploited the morphological variations in *Saccharomyces cerevisiae*—specifically the difference between single-peaked spherical and double-peaked budded cells. They established that the inertial focusing positions of these cells in straight rectangular microchannels are determined by their longitudinal axis dimensions, leading to a high-purity yeast isolation protocol. Furthermore, addressing the needs of marine bloom monitoring, Magalhães *et al.*¹¹ utilized the unique focusing characteristics of spiral-shaped microalgae to sort these organisms from complex seawater matrices, reporting a 90% separation efficiency.

Despite substantial advances in inertial focusing research, notable limitations persist. Current investigations predominantly center on the sorting of microparticles—often spherical or spheroidal to mimic cellular morphology—where lateral migration enables the separation of biological samples or industrial fluids based on size and intrinsic properties.¹² Consequently, applications such as flow cytometry have been optimized for these specific geometries, often overlooking the behavior of particles with complex morphological profiles. In practice, however, target entities frequently exhibit non-spherical shapes, such as rod-like bacteria¹³ or filamentous structures.¹⁴ These also include shape-memory polymers (SMPs), a class of stimuli-responsive materials capable of perceiving and adapting to environmental changes via programmed morphological shifts.¹⁵ Under specific stimuli—including thermal, optical, electrical, solvent, or magnetic activation—SMPs undergo predictable coiling deformations with magnitudes directly correlated with stimulus intensity.^{16–18} While SMPs offer advantages over conventional memory alloys and ceramics, such as lower density, greater deformation range, and diverse activation mechanisms, they are limited by lower mechanical strength and longer recovery times.¹⁹ These deficiencies are often mitigated by synthesizing shape-memory polymer composites (SMPCs) reinforced with functional particles or fibers,²⁰ rendering them promising for aerospace, biomedical devices, flexible electronics, and soft robotics.²¹ Specifically, micrometer-scale SMPs have been successfully utilized in drug delivery, regenerative medicine, and food-grade microcapsules, encompassing both artificial materials (e.g., hydrogels) and natural components (e.g., cells and subcellular compartments).²² However, critical questions remain regarding the fluid–structure interaction of such coiled filaments in channel flows. It is currently unclear whether inertial focusing principles can be effectively harnessed to manipulate and separate these complex, deformable structures, a problem that warrants further exploration.

Practical research has demonstrated that relying solely on experimental approaches with microfluidic chips makes it challenging to comprehensively capture the diverse motion patterns of particles in fluids. However, with advancements in computational power, numerical simulation technologies have matured significantly. Notably, the Immersed Boundary–Lattice Boltzmann Method (IB-LBM) has emerged as a primary methodology for investigating the underlying mechanisms of particle inertial focusing. By integrating the kinetic theory of the lattice Boltzmann method with the boundary enforcement capabilities of the Immersed

Boundary technique, the IB-LBM efficiently simulates complex fluid–solid interactions (FSIs) at the microscale, holding substantial promise for applications in biomedicine, chemical analysis, and micro/nano-processing.

This numerical framework has provided profound insights into inertial migration. In 2011, Shin and Sung²³ pioneered its application in two-dimensional Poiseuille flow, revealing how equilibrium positions are governed by the interplay between wall effects and shear gradients. Building on this, Kim *et al.*²⁴ developed a three-dimensional elastic particle model, confirming the decisive roles of wall-induced and shear gradient lift forces. Subsequent studies systematically examined the influence of key hydrodynamic parameters; for instance, Sun and Bo²⁵ demonstrated that higher Reynolds numbers drive particles to focus farther from the channel centerline, while Li *et al.*²⁶ established a comprehensive mathematical model to describe particle dynamics in combined focusing states. Research has since expanded to include multi-parameter coupling and complex channel configurations: Sun *et al.*²⁷ elucidated the mechanisms of self-rotation-induced lift forces relative to particle radius, while Jiang *et al.*²⁸ identified size-dependent focusing variations in symmetrical serpentine channels attributed to volume effects. More recently, Xu *et al.*²⁹ proposed a theory of combined focusing under external forces to enable active manipulation of particle behavior.

Despite extensive characterizations of non-spherical particles, critical gaps remain that limit the applicability of these models to realistic scenarios. Studies on rigid non-spherical particles effectively capture shape anisotropy but inherently neglect the complex fluid–structure interactions and large deformations induced by flow stresses. Conversely, investigations into straight flexible filaments account for deformation but fail to consider the profound influence of initial geometric curvature. In biological and industrial contexts—such as the transport of DNA, curved microswimmers, or SMP-based polymeric coils—filaments rarely conform to idealized rigid or straight geometries. The initial curvature introduces unique rotational dynamics and lateral migration mechanisms that cannot be predicted by simply extrapolating from straight or rigid models. Specifically, the distinct competition between a preset morphology and elastic bending resistance creates a dynamic regime that has been largely unexplored. Therefore, a systematic investigation into curved flexible filaments is essential not only to bridge this theoretical gap but also to establish a physical basis for the precise manipulation of deformable micro-objects.³⁰

Addressing these challenges, recent research has increasingly utilized numerical methods to handle microscale constraints and surface effects. Capitalizing on these capabilities, this study employs the Immersed Boundary–Lattice Boltzmann Method (IB-LBM) to establish a robust numerical model for investigating the inertial focusing of flexible filaments with initial curvature. By discretizing solid boundaries into virtual elastic grids and incorporating feedback forces within the LBM framework, the proposed model overcomes the limitations of traditional methods in accurately capturing microscale fluid dynamics. Specifically, a two-dimensional planar flow channel model is constructed to simulate curved fiber segments, which are modeled using Hooke's law of elasticity and Euler–Bernoulli beam theory. Based on this framework, a comprehensive analysis is performed to systematically investigate the effects of various parameters—including initial position, filament length,

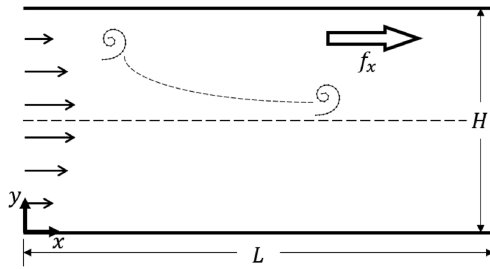


FIG. 1. Schematic diagram of inertial focusing flow channel.

degree of curvature, and curvature direction—on the focusing behavior of curved filaments.

II. INERTIAL FOCUSING MODEL OF CURVED FILAMENT

A. The inertial focusing model of the curved filaments

This paper investigates the inertial focusing behavior of a single crimped fiber segment within a fluid flow, with the computational model illustrated in Fig. 1. The microchannel is defined by a height of $H = 160 \mu\text{m}$ between the top and bottom walls and a length of $L = 300 \mu\text{m}$. Oriented horizontally, the channel facilitates fluid entry parallel to the streamwise direction from the left inlet and subsequent exit through the right outlet. The upper and lower boundaries of the computational domain are enforced as no-slip rigid walls, whereas the inlet and outlet borders are treated as periodic boundaries to effectively emulate infinite continuous flow conditions.

The fluid properties are defined as having a kinematic viscosity $\nu = 10^{-6} \text{ m}^2/\text{s}$ and a density $\rho = 10^3 \text{ kg/m}^3$. Initially, the flow field is stationary and is driven by a uniform body force f_x corresponding to a pressure difference ΔP . The simulation employs a time step $\Delta t = 2.0 \times 10^{-7} \text{ s}$ throughout the migration process. To ensure sufficient time for the filament to reach a stable focusing state, the total simulation time is set to $T = 0.4 \text{ s}$. Under these conditions, the flow field Reynolds number is determined to be $Re = u_0 H / \nu = 10$. The correspondence between lattice parameters and physical model parameters is provided in Table I.

B. The IB-LBM framework

This study employs the multiple-relaxation-time (MRT) lattice Boltzmann method (LBM) for numerical simulations. The D2Q9

lattice model was adopted, and the corresponding discrete lattice Boltzmann equation is given by³¹

$$g_i(x + e_i \Delta t, t + \Delta t) = g_i(x, t) - \hat{S}[g_i(x, t) - g_i^{eq}(x, t)] + F'_i, \quad (1)$$

where $g_i(x, t)$ is the particle distribution function, x denotes the spatial position vector, t represents time, e_i is the discrete velocity vector in the i th direction, Δt stands for the time step, $g_i^{eq}(x, t)$ denotes the equilibrium distribution function, F'_i represents the external force, and $\hat{S}$ represents the collision matrix. In the D2Q9 lattice model, the discrete velocity vectors $e_i = \{e_{ix}; e_{iy}\}$ have x-components $[1, 0, -1, 0, 1, -1, -1, 1, 0]$ and y-components $[0, 1, 0, -1, 1, 1, -1, -1, 0]$. The equilibrium distribution function $g_i^{eq}(x, t)$ is expressed as³²

$$g_i^{eq} = \omega_i \rho \left[1 + \frac{e_i \cdot u}{c_s^2} + \frac{uu : (e_i e_i - c_s^2 I)}{2c_s^4} \right], \quad (2)$$

where ω_i denotes the weighting coefficients for different lattice nodes, typically given by $\omega_0 = 4/9$, $\omega_i = 1/9$ ($i = 1, 2, 3, 4$), and $\omega_i = 1/36$ ($i = 5, 6, 7, 8$); c_s represents the speed of sound, defined as $c_s = 1/\sqrt{3}$; I expresses the unit matrix; ρ is the fluid density; and u is the macroscopic velocity, which are specifically expressed as³³

$$\rho = \sum_i g_i, \quad (3)$$

$$u = \frac{1}{\rho} \left(\sum_i g_i e_i + 0.5 f \Delta t \right), \quad (4)$$

where $f = (f_x, f_y)$ denotes the external force with components in two directions. The collision matrix $\hat{S}$ is typically expressed as $\hat{S} = M^{-1} S M$, where M denotes the coefficient matrix and S is the collision matrix in the velocity space. For the D2Q9 lattice model, S is given by³⁴

$$S = \text{diag}[s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9] = \text{diag}\left[1, 1.64, 1.54, 1, 1.9, 1, 1.9, \frac{1}{\tau}, \frac{1}{\tau}\right]. \quad (5)$$

Therefore, the external force term F'_i can be expressed as³⁵

$$F'_i = M^{-1} \left(\frac{I - S}{2} \right) M G_i. \quad (6)$$

The term G_i is determined by³⁵

$$G_i = \left(1 - \frac{1}{2\tau} \right) \omega_i \left[\frac{e_i \cdot u}{c_s^2} + \frac{e_i \cdot u}{c_s^4} e_i \right] \cdot f, \quad (7)$$

TABLE I. Correspondence between grid parameters and physical parameters.

Physical significance	Symbol	Dimensionless parameter value	Physical parameter values
Channel height	H	160	160 μm
Channel length	L	300	300 μm
Fluid kinematic viscosity	ν	0.2	$1.0 \times 10^{-6} \text{ m}^2/\text{s}$
Fluid density	ρ	1.0	$1.0 \times 10^3 \text{ kg/m}^3$
Uniform body force	f_x	8.0×10^{-5}	$2.0 \times 10^{-12} \text{ N}$
Total simulation time	T	2.0×10^6	0.4 s

where τ is the relaxation time. In addition, this study employs the immersed boundary method (IBM) to address the fluid–structure interaction problem of filament segments moving in a fluid. The effect of the solid boundary on the fluid is represented by introducing an additional force source term f , which is incorporated into the fluid governing equations. The influence of the solid boundary is described by the positions X of discrete points and the forces F acting on them, and the force is distributed into the fluid domain via the following formula:³⁶

$$f(x, t) = \int F(s, t) D(x - X(s, t)) ds, \quad (8)$$

$$U(s, t) = \int u(x, t) D(x - X(s, t)) dx, \quad (9)$$

where s denotes discrete points on the solid boundary, t represents time, $X(s, t)$, $U(s, t)$, and $F(s, t)$, respectively, denote the coordinates, velocities, and forces of the solid boundary points, and x , $u(x, t)$, and $f(x, t)$, respectively, represent the coordinates, velocity, and distributed force of a point in the fluid domain. The function $D(x - X)$ is a Dirac delta function, which can be expressed as³²

$$D(x - X) = \prod_{i=1}^n \delta(x_i - X_i), \quad (10)$$

where $\delta(x_i - X_i)$ denotes a discretized delta function,³² n denotes the total dimension of the model, x represents Lagrangian points on the immersed boundary, and X represents Eulerian points in the fluid domain. Lagrangian points and Eulerian points are spatially connected via the delta function, thereby achieving efficient coupling between the flow field and the solid boundary.

C. Mechanical model of curved filament

A single filament is initially released near the channel sidewall, featuring a helical structure with lengths $l = 24 \mu\text{m}$ and $l = 49 \mu\text{m}$. The filament's deformability and coiling characteristics are described by a “node-spring” model. With its density approximately matched to that of the fluid, the coiled morphology of the filament is determined by the curvature of each node. The mechanical behavior is primarily characterized by tangential tensile force F_s and curvature control force F_k , which can be expressed as

$$F(s, t) = F_s(s, t) + F_k(s, t). \quad (11)$$

Among these forces, $F_s(s, t)$ maintains the spacing between adjacent nodes along the filament boundary. According to Hooke's law of elasticity, this tensile force can be expressed as

$$F_s(s, t) = \frac{\partial}{\partial s} \left[K_s \left(\left| \frac{\partial X(s, t)}{\partial s} \right| - 1 \right) \left| \frac{\partial X(s, t)}{\partial s} \right| \right]. \quad (12)$$

Here, K_s represents the stretching coefficient, and $\partial X(s, t)/\partial s$ denotes the tangent vector, the magnitude of which is normalized to 1 to form the unit tangent vector. To achieve the filament segment with controlled bending curvature, a bending control force F_k is introduced and expressed as

$$F_k(s, t) = K_k (\kappa - \kappa_r) \vec{n}. \quad (13)$$

Here, κ_r is the desired curvature that defines the filament's target bending shape, $\vec{n}$ is the unit normal vector, and κ is the instantaneous curvature calculated as

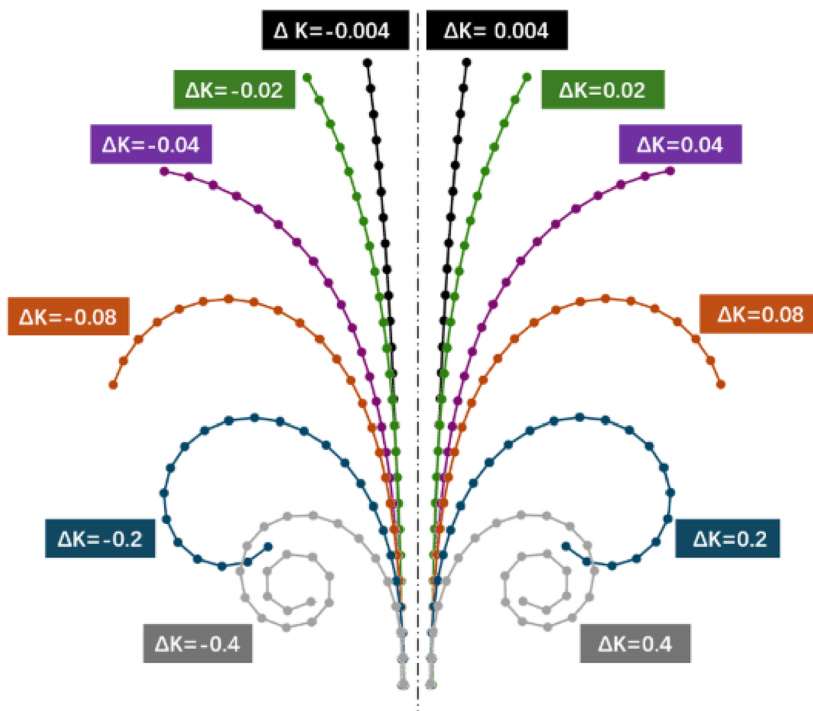


FIG. 2. Schematic diagram of the morphology of filaments with length $l = 24 \mu\text{m}$ under different curl coefficients.

TABLE II. Parameter settings for curved filaments.

Physical significance	Symbol	Dimensionless parameter value	Physical parameter values
Inter-node spacing	Δs	1	1 μm
Number of nodes	N	25–50	25–50
Length of curved filament	$\Delta s \times (N - 1)$	24–49	24–49 μm
Stretch coefficient	K_s	3	$3 \times 10^{-10} \text{ N} \cdot \text{m}$
Curvature control coefficient	K_κ	2	$2 \times 10^{-10} \text{ N} \cdot \text{m}$

$$\kappa = \frac{\ddot{y}\dot{x} - \ddot{x}\dot{y}}{(\dot{x}^2 + \dot{y}^2)^{3/2}}, \quad (14)$$

where x and y are the Cartesian coordinates of a node, while $\dot{x}$, $\dot{y}$ and $\ddot{x}$, $\ddot{y}$ denote the first and second derivatives with respect to the parametric coordinate, respectively.

D. Parameter settings

The morphologies of the curved flexible filaments are shown in Fig. 2.

The preconfigured filament adopts a helical shape with one-sided bending, characterized by a non-uniform curvature distribution across its nodes. The two ends of the filament are defined as the curved end and the straight end, respectively. Nodes near the curved end exhibit a high curvature, while those near the straight end have a low curvature. Nodes near the curved end exhibit high curvature, while those near the straight end have low curvature. Taking a 25-node segment as an example, the target curvature $\kappa_r(i)$ from the straight end ($i = 1$) to the curved end ($i = 25$) follows an arithmetic progression with common difference $\Delta\kappa$ such that $\kappa_r(i) = i \times \Delta\kappa$, where i denotes the node index, ranging from 1 to N . When the curvature parameter $\Delta\kappa = -0.004$, the resulting curl orientation corresponds to the left configuration of Fig. 2; when $\Delta\kappa = 0.004$, the curl appears as shown on the right side of Fig. 2.

Assuming an inter-nodal spacing of $\Delta s = 1$ along the curved filament, the geometric and structural parameters of the segment are summarized in Table II.

III. MODEL VALIDATION

A. Grid independence verification

In Immersed Boundary-Lattice Boltzmann Method (IB-LBM) simulations, mesh resolution critically governs the accuracy of numerical outcomes. This dependence stems from the ability of the discretization scheme to faithfully capture continuous physical phenomena. An excessively coarse mesh, characterized by insufficient spatial resolution, may obscure essential flow features and interface evolution. Consequently, this deficiency can distort particle trajectories, induce errors in fluid–structure interaction (FSI) forces, and culminate in numerical solutions that deviate significantly from actual physical behavior. Conversely, highly refined meshes, while capable of resolving finer flow structures, entail an exponential increase in computational nodes. This proliferation not only amplifies memory usage and processing time but also heightens susceptibility to numerical instabilities arising from accumulated

round-off errors, thereby compromising both simulation efficiency and practical applicability. For these reasons, mesh independence verification is an indispensable prerequisite for ensuring reliable and reproducible numerical results in complex FSI simulations.

Grid independence verification constitutes a systematic procedure focused on monitoring the convergence behavior of key physical quantities as grid resolution is progressively increased. In the specific context of IB-LBM simulations, particular emphasis must be placed on tracking the evolution of critical metrics, such as particle inertial focusing positions, velocity field distributions, and pressure gradients. The solution is deemed effectively grid independent when further refinements in resolution yield negligible variations in these computed quantities. This verification process not only validates the reliability of the numerical results but also establishes a rational basis for determining optimal spatial discretization strategies in subsequent investigations.

To perform grid independence verification, a mathematical model was developed in this study to simulate the free migration of a rigid circular particle with a radius of 5 μm in a two-dimensional straight microchannel under periodic flow conditions. The channel has a width $H = 60 \mu\text{m}$, a length $L = 180 \mu\text{m}$, and the flow is characterized by a Reynolds number $Re = 200$. The computational domain is discretized into 180 grids along the horizontal direction and 60 grids along the vertical direction, forming a planar model with a total of $N = 10\,800$ grids. This configuration corresponds to a grid spacing of $\Delta x = 1.00 \mu\text{m}$ and a grid density of $N_{grid} = 1.00 \text{ cells}/\mu\text{m}^2$. Here, N_{grid} denotes the number of grids per unit area in the plane and serves as a metric for quantifying the sparsity or density of the mesh in the model. In this study, N_{grid} is calculated using the following formula:

$$N_{grid} = \frac{N}{H \cdot L}, \quad (15)$$

where N denotes the total number of mesh elements in the planar model. The number of grid cells was uniformly increased in both horizontal and vertical directions to achieve grid densities of $N_{grid} = 1.00, 1.44, 1.96, 2.56, 3.24$, and $4.00 \text{ cells}/\mu\text{m}^2$. Circular rigid particles with a radius of 5 μm were released from the bottom edge of the channel. The steady-state inertial focusing position of the particle centroid, represented by both the radial coordinate Y and the normalized radial position Y/H , was recorded for each grid configuration. The corresponding results are summarized in Table III.

As the grid spacing Δx is systematically reduced from 1.00 to 0.50 μm , the corresponding focusing position Y decreases from 20.05 to 19.58 μm . This variation follows a monotonic decreasing

TABLE III. Inertial focusing positions of rigid particles (radius = 5 μm) under different mesh densities.

Grid spacing Δx (μm)	Number of horizontal grids	Number of vertical grids	Total number of mesh elements N	Mesh density N_{grid} ($\text{cells}/\mu\text{m}^2$)	Focusing radial position Y (μm)	Normalized focusing radial position Y/H
1.00	180	60	10 800	1.00	20.05	0.33
0.83	216	72	15 552	1.44	19.87	0.33
0.71	252	84	21 168	1.96	19.82	0.33
0.63	288	96	27 648	2.56	19.60	0.33
0.56	324	108	34 992	3.24	19.59	0.33
0.50	360	120	43 200	4.00	19.58	0.33

trend at a progressively decreasing rate, suggesting that the numerical solution is approaching convergence. The normalized focusing radial position Y/H remains constant at 0.33 across all grid configurations, further confirming that mesh density has a negligible influence on the simulated inertial focusing behavior of particles. Therefore, to balance computational efficiency and result reliability, a grid spacing $\Delta x = 1.00 \mu\text{m}$ ($N_{\text{grid}} = 1.00 \text{ cells}/\mu\text{m}^2$) is selected as the optimal discretization scheme for subsequent simulations.

B. Verification of inertial focusing of single rigid particles

Due to variations in experimental conditions, reported equilibrium positions of particles exhibit discrepancies across different references. By comparing numerical simulation results with existing experimental data, the capability of the numerical model to capture the underlying mechanism of inertial focusing can be validated. Such a comparative analysis enables a quantitative assessment of deviations between numerical predictions and empirical observations, facilitating the definition of the applicable range for the proposed model.

The physical principle of inertial focusing relies on the balance between wall-induced lift forces and shear gradient-induced lift forces, which collectively drive particles toward specific equilibrium positions within microchannels. To validate the single-particle inertial focusing model developed in this study, rigid particles are employed in the simulations. The inherent rigidity of these particles ensures a constant shape and volume during migration, thereby eliminating additional complexities in fluid–structure coupling that

may arise from morphological changes in flexible particles. Consequently, the inertial focusing behavior of rigid particles serves as a reliable benchmark for verifying the fundamental correctness of the numerical model.

To validate the inertial focusing behavior of a single rigid particle, this study establishes a two-dimensional straight microchannel with periodic boundary conditions, replicating the experimental setup described in Lashgari.³⁷ The microchannel has a width $H = 160 \mu\text{m}$ and a length $L = 480 \mu\text{m}$ and is discretized using a grid density $N_{\text{grid}} = 1.00 \text{ cells}/\mu\text{m}^2$. At a Reynolds number $Re = 100$, rigid particles with radii of 16, 32, and $46 \mu\text{m}$ are released from the same initial position near one side of the channel. The steady-state inertial focusing position of the particle centroid, represented by the radial coordinate Y , is recorded for each case. In addition, with the particle radius fixed at $R = 36 \mu\text{m}$, simulations are conducted at fluid Reynolds numbers $Re = 50, 100$, and 200 in the channel, with the particle released from the same lateral initial position. The corresponding focused equilibrium positions, Y , were observed in each scenario. A quantitative comparison between the present numerical results and the experimental data reported by Lashgari is provided in Table IV.

As presented in the comparison within Table IV, the reliability of the inertial focusing model is validated for a configuration featuring a channel height $H = 160 \mu\text{m}$, channel length $L = 480 \mu\text{m}$, and grid density $N_{\text{grid}} = 1.00 \text{ cells}/\mu\text{m}^2$. This validation is achieved by comparing the normalized equilibrium position Y/H obtained from the current numerical simulations with existing experimental data. At a Reynolds number $Re = 100$, results for varying particle radii exhibit excellent agreement with the reference values,

TABLE IV. Comparison of normalized inertial focusing positions (Y/H) of rigid particles: experiments vs simulations. All data are dimensionless values of Y/H , where Y is the focusing radial position and H is the channel width.

Parameter type	Parameter value	Experimental results (Y/H)	Simulation results (Y/H)
Different rigid particle radii (μm)	$R = 16 \mu\text{m}$	0.34	0.34
	$R = 32 \mu\text{m}$	0.30	0.31
	$R = 46 \mu\text{m}$	0.27	0.27
Different Reynolds numbers	$Re = 50$	0.29	0.32
	$Re = 100$	0.30	0.30
	$Re = 200$	0.31	0.29

yielding a maximum deviation of merely 0.01. Similarly, for both lower ($Re = 50$) and higher ($Re = 200$) Reynolds numbers, the numerical predictions demonstrate strong consistency with experimental measurements, showing deviations of 0.03 and 0.02, respectively. These findings confirm that the developed IB-LBM model accurately captures the fundamental behavior of particle inertial focusing, thereby demonstrating its predictive capability across varying flow conditions and particle sizes.

IV. INERTIAL FOCUSING CHARACTERISTICS OF CURVED FILAMENT

A. Migration characteristics of inertial focusing of curved filament

Based on the channel parameters and flow characteristics defined in Sec. I A, numerical simulations are conducted to investigate the migration trajectory of a curved filament of length $l = 49 \mu\text{m}$ in the fluid channel. The study examines four distinct curvature parameters: $\Delta\kappa = 0.4 \text{ m}^{-1}$, $\Delta\kappa = 0.04 \text{ m}^{-1}$, $\Delta\kappa = -0.2 \text{ m}^{-1}$, and $\Delta\kappa = -0.02 \text{ m}^{-1}$, with a sampling time step $\Delta t = 40 \mu\text{s}$. All curved filaments migrate within the region bounded by the channel midline and the upper wall of the channel, with their specific morphological configurations illustrated in Fig. 3.

The study reveals distinct migration behaviors of curved filaments depending on their degrees of curvature. Curved filaments with lower curvature and straighter morphologies, specifically those with $\Delta\kappa = 0.04 \text{ m}^{-1}$ and $\Delta\kappa = -0.02 \text{ m}^{-1}$, maintain relatively stable states in the channel and predominantly migrate along the main flow direction. In contrast, curved filaments with higher degrees of curvature, such as those with $\Delta\kappa = 0.4 \text{ m}^{-1}$ and $\Delta\kappa = -0.2 \text{ m}^{-1}$, exhibit

more complex dynamic behaviors. These filaments not only undergo morphological deformation but also exhibit systematic self-rotation when exposed to the channel flow. The rotational motion follows the characteristic pattern of Poiseuille flow, manifesting as counter-clockwise rotation above the channel midline and clockwise rotation below the channel midline.

Figure 3 provides a visual comparison of the morphological differences among curved filaments under various curvature parameters, as well as their corresponding dynamic characteristics in the fluid channel. The deformation and self-rotation of these curved filaments significantly influence their inertial focusing behavior, resulting in a non-steady-state equilibrium position rather than a fixed focusing position.

Unlike granular particles, curved filaments undergo substantial morphological and positional changes under flow fields. To quantitatively describe the positional evolution in inertial focusing, this study monitors the longitudinal movement of the equivalent center of curved filaments throughout their migration trajectory. The centroid, designated as X_c , is defined as

$$X_c = \frac{1}{n} \sum_{i=1}^n X_i, \quad (16)$$

where X_i denotes the position vector of the i th node along the curved filament and X_c represents the centroid position vector with Cartesian coordinates (x_c, y_c) . The lateral focusing position of the filament in the channel is characterized by its y_c -coordinate. Figure 4 shows the temporal evolution of y_c for a curved filament of length $l = 50 \mu\text{m}$ and curvature parameter $\Delta\kappa = 0.2 \text{ m}^{-1}$, confined in a microchannel of width $H = 160 \mu\text{m}$.

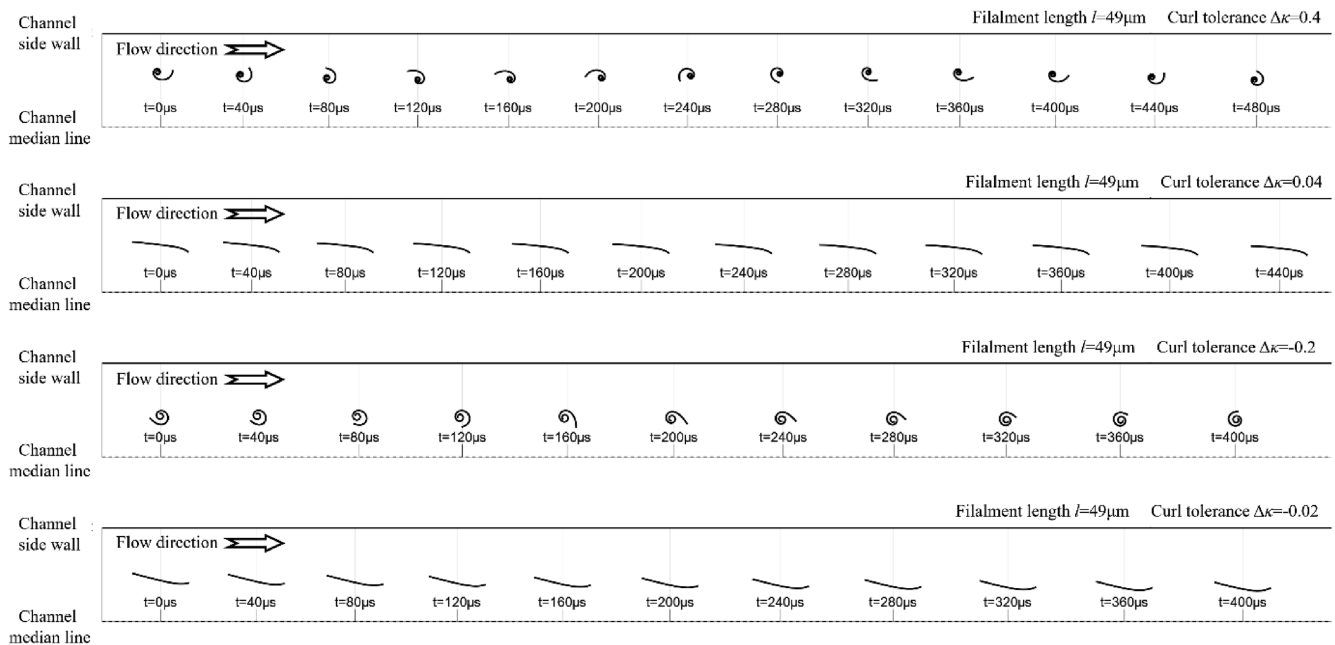


FIG. 3. Migration timeline of curved filaments with four types of curling tolerances $\Delta\kappa$ in the channel.

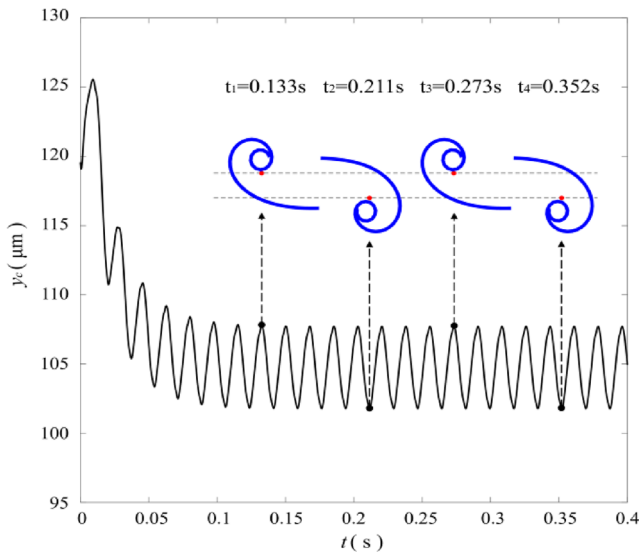


FIG. 4. Temporal evolution of the longitudinal centroid position (y_c) for a curved filament.

As shown in Fig. 4, the curved filament gradually enters a stable periodic motion ~ 0.4 s after its release. Owing to the morphological asymmetry of the filament, its focusing position exhibits regular oscillations during rotation.

B. Verification of initial position independence for curved filaments

In the study of the inertial focusing behavior of individual curved filaments, the initial release position serves as a key initial

condition for analyzing their subsequent dynamics. Given the typical Poiseuille flow characteristics within the channel, the velocity distribution varies significantly along the radial direction across different starting positions, and this variation may theoretically influence the initial forces acting on the filament, its migration trajectory, and its final equilibrium state. Moreover, the initial shape and position of the filament may further modulate its dynamic behavior via complex near-wall interactions with the channel walls.

To systematically quantify the potential effect of the initial position on the inertial focusing of curved filaments, a series of controlled experiments was designed. In these experiments, two curved filaments with different curvature tolerances ($\Delta\kappa = 0.08 \text{ m}^{-1}$ and $\Delta\kappa = 0.20 \text{ m}^{-1}$) were selected. Both filaments had the same length, $l = 24 \text{ } \mu\text{m}$, and an elastic bending coefficient of $K_\kappa = 2.0 \times 10^{-10} \text{ N} \cdot \text{m}$. All other channel parameters remained unchanged, with channel width $H = 160 \text{ } \mu\text{m}$.

To systematically investigate the influence of the initial position, individual curved filaments were released from ten distinct radial positions along the vertical direction of the channel cross section. These release points were symmetrically distributed with respect to the channel centerline ($y = 80 \text{ } \mu\text{m}$), specifically at $y = 14, 27, 40, 53, 66, 93, 106, 119, 132$, and $146 \text{ } \mu\text{m}$. By tracking the longitudinal centroid position y_c as a function of downstream migration distance (Fig. 5), the dynamic process of equilibrium attainment and the consistency of the final focusing state were analyzed. All curved filaments exhibited well-defined focusing behavior within the channel. The inertial focusing interval Q of the trajectories and the rotational period T were statistically determined for each initial position, as summarized in Table V.

In Table V, curved filaments released from different focus positions (with $\Delta\kappa = 0.08 \text{ m}^{-1}$ and $\Delta\kappa = 0.20 \text{ m}^{-1}$) consistently exhibit pronounced inertial focusing. For filaments with $\Delta\kappa = 0.08 \text{ m}^{-1}$ released above the channel centerline (focus positions $y_0 = 146, 132$,

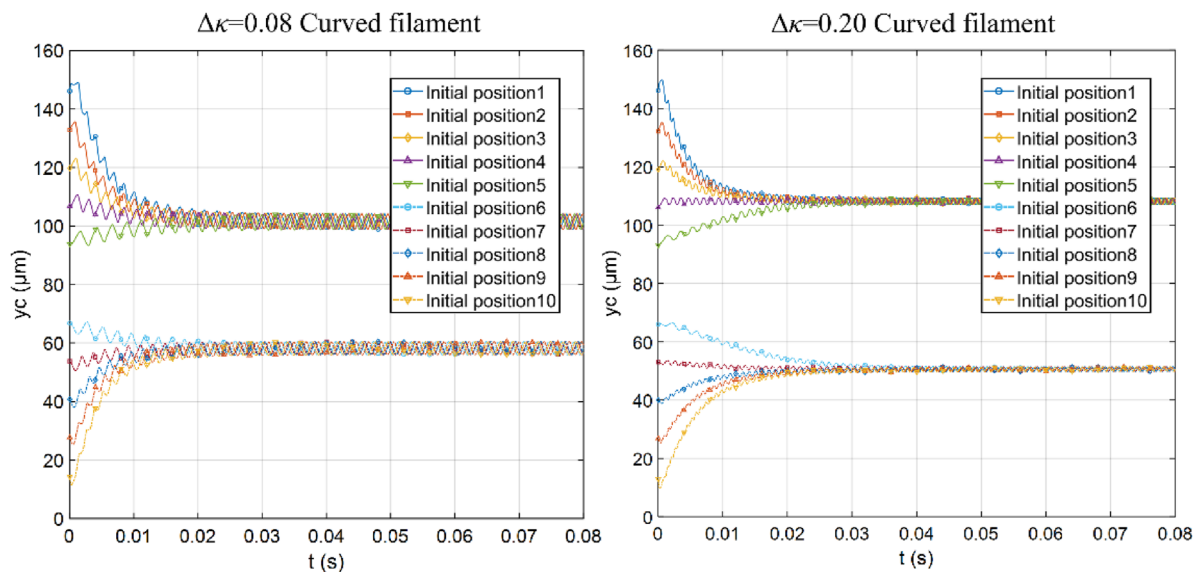


FIG. 5. Inertial focusing intervals and rotation periods of single curved filaments at different focus positions.

TABLE V. Inertial focusing intervals and rotation periods of single curved filaments at different focus positions.

Initial release position y_0 (μm)	Focus interval Q (μm) ($\Delta\kappa = 0.08 \text{ m}^{-1}$)	Normalized midpoint Y/H ($\Delta\kappa = 0.08 \text{ m}^{-1}$)	Rotation period T (ms) ($\Delta\kappa = 0.08 \text{ m}^{-1}$)	Focus interval Q (μm) ($\Delta\kappa = 0.20 \text{ m}^{-1}$)	Normalized midpoint Y/H ($\Delta\kappa = 0.20 \text{ m}^{-1}$)	Rotation period T (ms) ($\Delta\kappa = 0.20 \text{ m}^{-1}$)
146	[98.79, 104.08]	0.360	2.01	[107.02, 109.39]	0.324	1.23
132	[98.79, 104.08]	0.360	2.02	[107.02, 109.39]	0.324	1.23
119	[98.79, 104.08]	0.360	2.02	[107.02, 109.39]	0.324	1.23
106	[98.79, 104.08]	0.360	2.02	[107.02, 109.39]	0.324	1.23
93	[98.79, 104.08]	0.360	2.03	[107.02, 109.39]	0.324	1.22
66	[56.05, 60.49]	0.364	1.95	[49.91, 51.44]	0.317	1.06
53	[56.05, 60.49]	0.364	1.95	[49.91, 51.44]	0.317	1.05
40	[56.05, 60.49]	0.364	1.95	[49.91, 51.44]	0.317	1.04
27	[56.05, 60.49]	0.364	1.95	[49.91, 51.44]	0.317	1.04
14	[56.05, 60.49]	0.364	1.94	[49.91, 51.44]	0.317	1.04

119, 106, and 93 μm), all eventually converge to the same focusing interval $Q = [98.79, 104.08] \mu\text{m}$, corresponding to a normalized midpoint of the focusing interval $Y/H = 0.360$, with a stable rotation period $T \approx 2.01$ ms. Similarly, when released below the channel centerline ($y_0 = 66, 53, 40, 27$, and $14 \mu\text{m}$), they converge to $Q = [56.05, 60.49] \mu\text{m}$ ($Y/H = 0.364$) and exhibit a stable rotation period $T \approx 1.95$ ms. For filaments with $\Delta\kappa = 0.20 \text{ m}^{-1}$, a comparable trend is observed: those released above the centerline focus in $Q = [107.02, 109.39] \mu\text{m}$ ($Y/H = 0.324$), with $T \approx 1.23$ ms, while those released below the centerline focus in $Q = [49.91, 51.44] \mu\text{m}$ ($Y/H = 0.317$), with $T \approx 1.04$ ms.

These results demonstrate that despite substantial differences in their initial radial positions, curved filaments released from the same side of the channel centerline converge to an identical final inertial focusing state, including both the focusing interval and the rotation period. This observation confirms that the steady-state focusing behavior of a curved filament is determined solely by its intrinsic physical properties and the characteristics of the channel flow field, and is independent of its initial release position.

V. FACTORS INFLUENCING THE INERTIAL FOCUSING OF CURVED FILAMENTS

A. Effect of filament length on inertial focusing

To investigate the influence of filament length on inertial focusing behavior, a curved filament with length $l = 20 \mu\text{m}$, curvature parameter $\Delta\kappa = 0.20 \text{ m}^{-1}$, and curvature control coefficient $K_\kappa = 2.0 \times 10^{-10} \text{ N} \cdot \text{m}$ was used as the reference model. Scaled filaments with lengths $1.5l$, $2l$, $2.5l$, and $3l$ were generated by proportional scaling with factor λ (where $\lambda = 1.5, 2, 2.5, 3$), while maintaining a constant inter-node spacing $\Delta s = 1 \mu\text{m}$. The increase in filament length was achieved by increasing the number of nodes. During scaling, the curvature distribution was updated to $\kappa_r'(i) = \kappa_r(i)/\lambda$, where $\kappa_r(i) = i\Delta\kappa$ represents the curvature distribution of the reference curved filament. This approach ensures similar curvature geometry among filaments of different lengths while preserving the constant inter-node spacing.

Simulations were conducted in a two-dimensional channel of width $H = 160 \mu\text{m}$, length $L = 300 \mu\text{m}$, and grid density

$N_{\text{grid}} = 1.00 \text{ cells}/\mu\text{m}^2$, at a Reynolds number $Re = 10$. Curved filaments of lengths l , $1.5l$, $2l$, $2.5l$, and $3l$ were released from the same initial position on one side of the channel. The inertial focusing behavior of each filament was recorded based on the radial centroid coordinate y . As shown in Fig. 6 and Table VI, the results illustrate the focusing positions and their variation with filament length.

As shown in Fig. 6(a) and Table VI, the inertial focusing position of curved filaments exhibits a clear dependence on length, shifting significantly toward the channel centerline as l increases from 20 to 60 μm . Quantitatively, the normalized midpoint of the focusing interval (Y/H) decreases by 12.2%, moving from 0.320 ($l = 20 \mu\text{m}$) to 0.359 ($l = 6 \mu\text{m}$). Concurrently, the width of the focusing interval (Q) expands markedly by a factor of ~ 3.0 , rising from 2.33 to 7.63 μm . Furthermore, the rotation period T prolongs substantially, nearly doubling from 1.11 to 2.15 ms (an increase of 93.7%). This behavior stems primarily from the influence of filament geometry on hydrodynamic interactions: longer filaments exhibit a larger projected area during rotation, which amplifies the periodic variation in wall-induced repulsive forces and shear gradient-induced lift forces, leading to the observed expansion in the radial oscillation range. In addition, the increased length shifts the mass distribution farther from the axis of rotation, increasing the moment of inertia and reducing the filament's rotational responsiveness to fluid-driven torques, thereby accounting for the extended rotation period.

B. Effect of filament curvature on inertial focusing

To investigate the influence of filament curvature on inertial focusing, a curved filament with length $l = 50 \mu\text{m}$ and curvature control coefficient $K_\kappa = 2.0 \times 10^{-10} \text{ N} \cdot \text{m}$ was selected as the baseline model. The degree of curvature was controlled by adjusting the curvature parameter $\Delta\kappa$, which directly determines the filament's intrinsic bending shape in the stress-free state. Specifically, the intrinsic curvature distribution is defined by $\Delta\kappa$ and manifests as an arithmetic sequence from the straight end to the curved end, thereby precisely characterizing the filament's bending geometry. Filaments with nine different curvature tolerances ($\Delta\kappa = 0.08, 0.12, 0.16, 0.20, 0.24, 0.28, 0.32, 0.36$, and 0.40 m^{-1}) were simulated to systematically analyze the effect of curvature on focusing behavior.

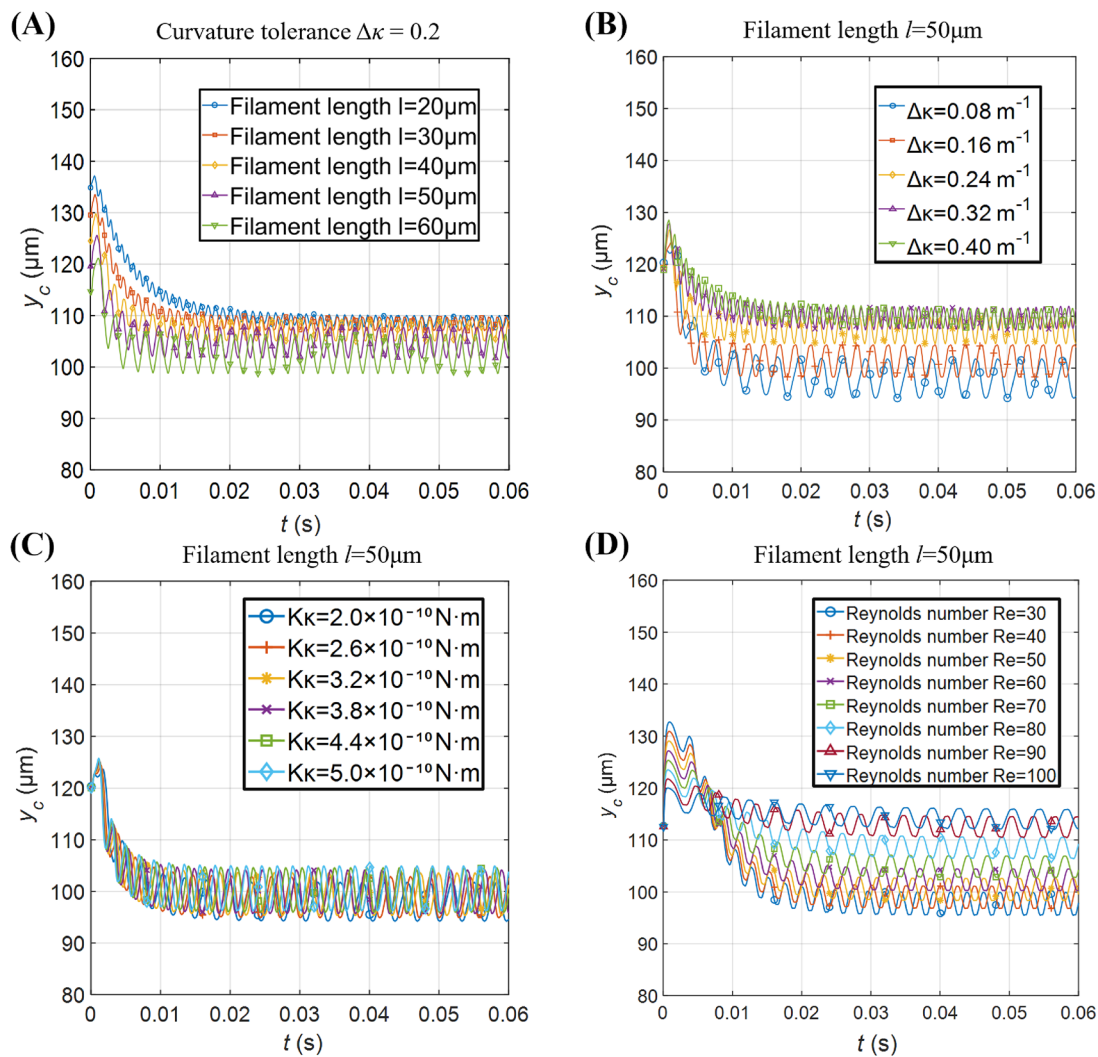


FIG. 6. Comprehensive effects of intrinsic curvature and bending rigidity on the inertial focusing of curved flexible filaments. (a) Temporal evolution of the cross-stream inertial focusing position for curved filaments of different lengths. (b) Time evolution of the cross-stream focusing position for curved filaments. (c) Time evolution of cross-stream inertial focusing positions for curved filaments with different bending stiffnesses. (d) Temporal trend of inertial focusing positions for curved filaments at different channel Reynolds numbers with different intrinsic curvature parameters.

TABLE VI. Inertial focusing intervals and rotation periods of curved filaments with different lengths.

Curved filament length l (μm)	Focus interval Q (μm)	Normalized midpoint of focusing interval Y/H	Rotation period T (ms)
20	[107.71, 110.04]	0.320	1.11
30	[107.07, 109.72]	0.323	1.20
40	[105.06, 109.10]	0.331	1.42
50	[101.75, 107.71]	0.345	1.76
60	[98.74, 106.37]	0.359	2.15

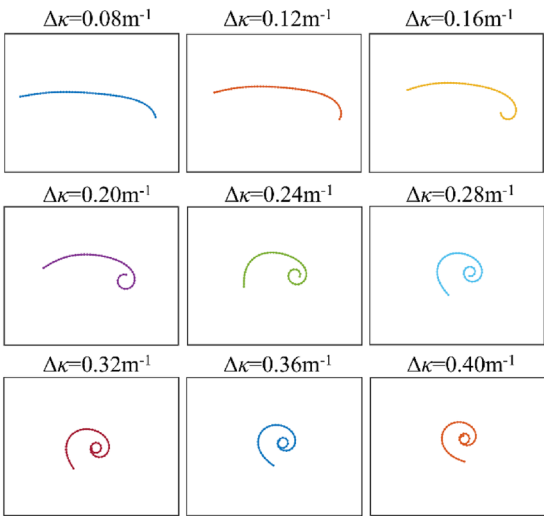


FIG. 7. Schematic of curved filaments with different intrinsic curvature parameters ($\Delta\kappa$).

Figure 7 illustrates the equilibrium morphologies of curved filaments under different intrinsic curvature parameters ($\Delta\kappa$) under no external flow conditions. As $\Delta\kappa$ increases from 0.08 to 0.40 m^{-1} , the filament shape evolves from a nearly straight configuration to a tightly wound spiral, which demonstrates a progressive increase in intrinsic curvature.

The simulations were conducted in a two-dimensional channel (width $H = 160\text{ }\mu\text{m}$, length $L = 300\text{ }\mu\text{m}$) with a grid resolution of $N_{\text{grid}} = 1.00\text{ cells}/\mu\text{m}^2$ and a Reynolds number of $Re = 10$. Filaments with varying curvature were released from the same initial position at the channel inlet, and their inertial focusing behavior was characterized by tracking the centroid position y in the channel's cross section. The corresponding results are presented in Fig. 6(b) and Table VII.

Figure 6(b) and Table VII quantify how intrinsic curvature governs the dynamics of curved filaments. As the dimensionless curvature rises from 0.08 to 0.40, the normalized focusing midpoint migrates outward from the channel centerline, shifting backward from 0.387 to 0.308. This stiffening of the filament shape concurrently compresses the spatial distribution, narrowing the focusing interval width by 50.0%, from 7.54 to 3.77 μm . Furthermore, the rotational dynamics accelerate significantly, with the period

shortening by 65.4% from 3.21 to 1.11 ms. Physically, these trends originate from the transition in filament morphology, which reshapes the surrounding flow field to alter the net force balance via changed pressure distribution and wake vortex structures. Low-curvature filaments adopt an extended posture, which enlarges the effective profile near the channel wall. The extended conformation squeezes the flow gap between the filament and the wall, creating a lower-pressure zone in the gap that amplifies the net wall-induced repulsive force pushing the filament toward the channel center. The asymmetric near-wall geometry also breaks the symmetry of the wake vortex structure, further enhancing this lateral force bias, while their distributed mass increases the moment of inertia, resulting in the prolonged rotation period. Conversely, highly curved filaments exhibit a compact, near-symmetric form farther from the wall. This greatly reduces the cross-filament pressure difference and maintains a nearly symmetric wake vortex structure, leading to a much weaker net lateral hydrodynamic force. Their reduced variation in wall proximity and concentrated mass distribution stabilize the hydrodynamic forces, yielding a tighter focusing band. In addition, this compaction lowers the moment of inertia, rendering the filament more agile to fluid-driven torques and facilitating the observed rapid rotation.

C. Influence of filament elasticity on inertial focusing

To examine the effect of elastic properties on the inertial focusing of curved filaments, a reference configuration was adopted with filament length $l = 50\text{ }\mu\text{m}$, stretching coefficient $K_s = 3.0 \times 10^{-10}\text{ N}\cdot\text{m}$, and intrinsic curvature parameter $\Delta\kappa = 0.12\text{ m}^{-1}$. The key variable in this study is the bending rigidity coefficient K_κ , which directly governs the filament's elastic behavior in the flow. As K_κ increases, the filament exhibits greater resistance to bending and faster elastic recovery. These differences in mechanical response affect the dynamic morphology of the filament during its transport through the channel, thereby influencing its final inertial focusing position. Six values of K_κ were selected: 2.0, 2.6, 3.2, 3.8, 4.4, and $5.0 \times 10^{-10}\text{ N}\cdot\text{m}$, to systematically evaluate the role of the filament's elasticity.

The simulations were performed in a two-dimensional channel with width $H = 160\text{ }\mu\text{m}$, length $L = 300\text{ }\mu\text{m}$, and grid resolution $N_{\text{grid}} = 1.00\text{ cells}/\mu\text{m}^2$, under a constant Reynolds number of $Re = 10$. Filaments with varying bending rigidity were released from the same initial position at the inlet, and their cross-stream focusing behavior was characterized by tracking the centroid coordinate y . The results are presented in Fig. 6(c) and Table VIII.

TABLE VII. Inertial focusing intervals and rotation periods of curved filaments with different intrinsic curvatures.

Curvature parameter $\Delta\kappa\text{ (m}^{-1}\text{)}$	Focus interval $Q\text{ (}\mu\text{m)}$	Normalized midpoint of focusing interval Y/H	Rotation period $T\text{ (ms)}$
0.08	[94.24, 101.78]	0.387	3.21
0.16	[98.31, 104.48]	0.366	2.26
0.24	[104.71, 109.82]	0.330	1.46
0.32	[107.65, 111.96]	0.314	1.21
0.40	[108.78, 112.55]	0.308	1.11

TABLE VIII. Inertial focusing intervals and rotational periods of curved filaments with different bending stiffnesses (K_κ).

Bending stiffness coefficient K_κ ($\times 10^{-10}$ N·m)	Focusing interval Q (μm)	Normalized midpoint of focusing interval Y/H	Rotation period T (ms)
2.0	[94.76, 102.52]	0.383	2.89
2.6	[94.89, 102.84]	0.382	2.85
3.2	[95.35, 103.59]	0.378	2.62
3.8	[95.71, 104.15]	0.375	2.46
4.4	[95.99, 104.57]	0.373	2.33
5.0	[96.24, 104.93]	0.371	2.23

Figure 6(c) and Table VIII elucidate the influence of bending stiffness on inertial migration. As the stiffness coefficient (K_κ) escalates from 2.0×10^{-10} to 5.0×10^{-10} N·m, the normalized focusing midpoint migrates outward by 3.1% from 0.383 to 0.371, moving incrementally away from the channel centerline. Concurrently, the spatial distribution of the filaments widens, with the focusing interval expanding from 7.76 to 8.69 μm , marking a 12.0% increase in bandwidth. Rotational dynamics also accelerate, with the period shortening from 2.89 to 2.23 ms—a 22.8% reduction in cycle duration. These trends are rooted in the interplay between structural rigidity and hydrodynamic forces. More compliant filaments (lower K_κ) readily deform, creating a larger effective profile near the wall that amplifies wall-induced repulsion and drives the centroid closer to the centerline. Conversely, stiffer filaments resist this deformation, maintaining a stable morphology with a more concentrated mass distribution and a reduced moment of inertia, which facilitates faster rotation. Despite these measurable shifts, the net displacement of the focusing position is confined within 0.012 in the normalized coordinates, indicating that bending stiffness exerts a second-order influence compared to geometric parameters like length and curvature.

D. Effect of channel Reynolds number on inertial focusing of curved filaments

To examine the influence of the channel Reynolds number (Re) on the inertial focusing of curved filaments, a reference configuration was selected with filament length $l = 50$ μm , stretching stiffness $K_s = 3.0 \times 10^{-10}$ N·m, bending stiffness $K_\kappa = 2.0 \times 10^{-10}$ N·m, and curvature tolerance $\Delta\kappa = 0.2$ m^{-1} . The key variable in this study is the Reynolds number (Re), a dimensionless parameter in fluid mechanics that characterizes the ratio of inertial to viscous forces, defined as

$$Re = \frac{LU}{\nu} = \frac{\rho LU}{\mu}, \quad (17)$$

where L denotes the characteristic length scale, U denotes the characteristic velocity, ν denotes the kinematic viscosity, μ denotes the dynamic viscosity, and ρ denotes the fluid density. The value of Re determines the flow regime: at low Re , the flow is laminar, characterized by smooth, layered motion; as Re increases, the flow transitions to a wavy and unstable state; and at high Re , the flow

becomes turbulent, characterized by chaotic vortices and irregular motion.

To systematically investigate the effect of Re on inertial focusing while ensuring the flow remains in the laminar regime, nine Reynolds numbers were tested: $Re = 20, 30, 40, 50, 60, 70, 80, 90$, and 100. The selection of this Re range is based on the typical working conditions of inertial focusing experiments in conventional microfluidic chips, which covers the finite inertia regime where inertial lift effects are non-negligible. This experiment aims to reveal the influence of Re on the focusing position, accuracy, and rotational period of curved filaments. The simulations were performed in a two-dimensional channel (width $H = 160$ μm , length $L = 300$ μm) with a grid resolution of $N_{grid} = 1.00$ cells/ μm^2 . Filaments with varying curvatures were released from the same initial position at the channel inlet, and their inertial focusing behavior was characterized by tracking the centroid position y in the channel's cross section. It should be noted that the conclusions drawn in this section are applicable within the tested 2D laminar weakly inertial regime, and extension to high- Re turbulent flows or three-dimensional microchannel scenarios requires further verification. The results are presented in Fig. 6(d) and Table IX.

Figure 6(d) and Table IX quantify the dependence of filament dynamics on the channel Reynolds number (Re). As Re escalates from 30 to 100, the focusing midpoint undergoes a substantial outward shift, migrating from 0.389 to 0.288, which corresponds to a 26.0% displacement away from the channel centerline. This hydrodynamic stiffening simultaneously compresses the spatial distribution, narrowing the focusing interval width by 37.8%, from 4.42 to 3.84 μm . Furthermore, the rotational period exhibits a monotonic increase, lengthening from 2.38 to 3.85 ms. Physically, these trends reflect the dominance of inertial effects at higher flow rates. At low Re , the mild velocity gradient yields a weaker shear-induced lift force and insufficient fluid drag to significantly deform the filament. This results in a compact morphology with a lower moment of inertia, fostering faster rotation and a resting position closer to the channel center. Conversely, high Re conditions intensify the velocity gradient and fluid impact. The resulting shear-induced lift forces are sufficiently strong to stretch the filament, effectively increasing its moment of inertia and driving the equilibrium position toward the wall. While the increased Re enhances focusing stability—evidenced by the narrowed band—the hydrodynamic stretching fundamentally increases the rotational resistance, accounting for the extended period.

TABLE IX. Inertial focusing intervals and rotation periods of curved filaments under different channel Reynolds numbers.

Channel Reynolds number Re	Focusing interval Q (μm)	Normalized midpoint of focusing interval Y/H	Rotation period T (ms)
30	[95.49, 99.91]	0.389	2.38
40	[96.78, 101.12]	0.382	2.47
50	[98.33, 102.58]	0.372	2.57
60	[100.24, 104.42]	0.360	2.67
70	[102.76, 106.89]	0.345	2.78
80	[106.41, 110.51]	0.322	2.90
90	[110.46, 114.49]	0.297	3.11
100	[112.05, 115.89]	0.288	3.85

VI. CONCLUSION

Employing the immersed boundary-lattice Boltzmann method (IB-LBM), this study establishes a two-dimensional model to investigate the inertial focusing of curved filaments within a straight microchannel. We systematically examined the effects of filament length, curvature, elasticity, and the channel Reynolds number. The results indicate that increasing filament length shifts the equilibrium position toward the channel centerline, broadens the focusing distribution, and prolongs the rotation period. Highly curved filaments, adopting a compact morphology, focus farther from the centerline with a tighter band and faster rotation. In contrast, elasticity exerts a relatively minor influence, causing only slight outward shifts and minor changes in rotation. Furthermore, higher Reynolds numbers—associated with steeper velocity gradients—drive focusing positions outward, compress the focusing interval, and increase rotational periods. These insights clarify the multi-factor mechanisms guiding filament transport.

Crucially, our analysis reveals a broader physical competition between geometric curvature and elastic effects. The geometric effect prevails when initial curvature is sufficiently high, preserving a compact, rigid-like morphology that minimizes wall interaction and facilitates rapid focusing. Conversely, elastic effects dominate in low-curvature configurations; here, the extended posture amplifies wall-induced repulsive forces and rotational inertia, thereby dictating lateral migration. The transition between these regimes is thus governed by the ratio of initial curvature to the filament’s susceptibility to flow-induced deformation, rather than stiffness alone. This universal law provides a fundamental physical basis for manipulating filament transport in microfluidic systems through precise geometric tailoring.

It should be noted that all conclusions related to the influence of Re in this study are applicable only within the tested range of $20 \leq Re \leq 100$, which covers the steady laminar weakly inertial regime matching the common working conditions of inertial microfluidics. The revealed Re -dependent focusing law has clear limitations when extended to other Re ranges: when Re exceeds 100 and the flow enters transition or turbulent regime, chaotic flow fluctuations and altered inertial lift distribution will significantly change the migration and focusing dynamics of curved filaments, which has not been covered in this study and requires further systematic investigation. In addition, the current model is

based on a two-dimensional channel assumption, and the characteristic length definition of Re and the corresponding wall confinement effect in three-dimensional microchannels are different from the 2D condition, so the generalizability of the obtained Re influence law still needs further experimental and numerical verification.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Qi Wang: Conceptualization (supporting); Investigation (lead); Methodology (equal); Resources (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yuan-Qing Xu:** Conceptualization (lead); Funding acquisition (lead); Investigation (equal); Methodology (lead); Resources (equal); Supervision (lead); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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