

Chaotic Mixing Enhancement in Microfluidic Channels with Time-Varying Geometric Perturbations

N.Rajasekaran

Assistant Professor, Department of Computer Science, Christ (Deemed to be University)

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Author's Email:

rajasekaran.n@christuniversity.in

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ABSTRACT

Microfluidic mixing is difficult because microscale flows remain laminar, which slows homogenization and limits interfacial transport. This is a key issue in lab-on-chip systems, biochemical assays, and compact reaction devices that require rapid mixing. Recent micromixer studies have shown that passive geometric features such as grooves, baffles, and wavy walls can improve mixing by enhancing interface stretching and secondary flow formation. However, most existing designs still rely on static channel geometries, which restrict the flow to a fixed transport pattern. A key gap therefore lies in understanding whether time-varying geometric perturbations can generate stronger chaotic advection than conventional fixed-wall micromixers. This article numerically investigates chaotic mixing in a microfluidic channel with dynamic geometric perturbations and evaluates the effects of perturbation amplitude and actuation frequency on concentration evolution and mixing efficiency. The results show that time-dependent channel deformation improves mixing within an optimal perturbation range, making it a promising strategy for compact high-performance micromixer design.

Author Orcid: 0009-0004-3382-7597

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1. INTRODUCTION

Microfluidic devices operate under low-Reynolds-number conditions, where viscous forces dominate and fluid streams tend to remain laminar over short channel lengths. Because of this, molecular diffusion alone often becomes too slow for rapid homogenization inside compact microchannels. The importance of efficient microscale mixing has therefore been emphasized in recent reviews of micromixer design and application, particularly for biochemical assays, lab-on-chip systems, and reaction engineering [1]. Modern summaries of micromixer development have also shown that mixing performance remains one of the main constraints in practical microfluidic integration, especially when device size must stay small and reagent consumption must remain low [2]. More detailed discussions of microscale transport physics further explain that successful mixing in such environments depends on repeated interface stretching, transverse transport,

and controlled advection rather than simple diffusion alone [3]. A broader review of current micromixer technologies also confirms that geometric manipulation of the internal flow is still one of the most effective routes for improving mixing under laminar conditions [4].

Passive micromixers are especially attractive because they do not require external fields, moving actuators, or complicated auxiliary systems. Instead, they rely on channel shape, embedded obstacles, grooves, bends, or expansion-contraction regions to redistribute the flow and enlarge the contact interface between fluid streams. This makes them easier to miniaturize and often simpler to fabricate than actively driven systems, a point repeatedly highlighted in recent micromixer reviews [5]. At the same time, comparative assessments of active and passive designs show that passive devices remain highly competitive when compactness, robustness, and low power demand are important design goals [1]. Structural overviews of state-of-the-art

micromixers also indicate that different geometries produce very different levels of mixing because each layout creates a distinct pattern of recirculation, deformation, and fluid exchange across the channel cross-section [2]. These observations suggest that geometry is not merely a supporting feature of the device but a primary driver of transport performance.

Despite the advances made with static channel structures, many passive micromixers still depend on fixed geometric arrangements that generate the same flow topology throughout operation. This limits their adaptability because the same internal structure may not maintain strong mixing over changing residence times, operating conditions, or transport requirements. Discussions of micromixing fundamentals have pointed out that chaotic advection becomes stronger when fluid elements experience repeated stretching and folding through spatially varying velocity gradients [3]. Reviews focused on innovative micromixer concepts similarly note that more aggressive geometric reorientation can intensify transverse motion and break the symmetry of laminar co-flow [4]. However, most existing studies continue to emphasize permanently embedded features rather than geometries that vary with time. This leaves an important research gap in the design of microchannels whose effective shape changes dynamically during the mixing process.

The present study addresses that gap by examining chaotic mixing enhancement in microfluidic channels with time-varying geometric perturbations. The core idea is that a temporally changing channel boundary can repeatedly reorganize the local strain field, disturb the fluid interface, and generate stronger advection-driven homogenization than a conventional static channel. In this article, the flow field and scalar transport are numerically resolved in a perturbed microchannel, and the influence of perturbation amplitude and actuation frequency is evaluated through concentration-field patterns and quantitative mixing metrics. The study therefore aims to establish a physically clear link between dynamic geometric modulation and microscale chaotic mixing performance, while also providing a compact framework suitable for next-generation lab-on-chip mixing design.

2. METHODOLOGY

The computational model is based on a two-inlet, one-outlet planar microchannel in which the central mixing region is subjected to a prescribed time-

varying geometric perturbation. Two miscible liquid streams enter the channel separately and form an initially stratified interface at the entrance of the perturbation zone. The baseline concept draws from recent micromixer studies showing that geometric features such as Z-shaped baffles can induce chaotic transport by disturbing the otherwise orderly laminar flow field [6]. Other recent designs using wavy channel walls and embedded obstacles have further demonstrated that controlled geometric irregularity can enhance interface distortion and mixing efficiency over a wide operating range [7]. Additional passive micromixer studies have also shown that compact structural modifications can yield strong mixing even under low-flow conditions, which supports the use of geometry-focused enhancement strategies in the present work [8]. On this basis, the present channel is modeled as a dynamically perturbed geometry rather than a fixed one.

The working fluid is assumed to be incompressible and Newtonian, and the flow remains laminar because the characteristic microchannel dimensions and inlet conditions correspond to low Reynolds number transport. The fluid motion is governed by the continuity equation and the incompressible Navier-Stokes equations, while scalar mixing is represented through a convection-diffusion transport equation. This type of coupled formulation is standard in recent numerical micromixer studies, including chamber-based chaotic passive mixers where geometry-driven flow reorganization strongly affects species distribution [9]. Similar transport modeling has also been used in groove-based chaotic micromixers, where reversed ridge and groove patterns alter local advection pathways and improve scalar homogenization [10]. In the present formulation, the same general transport framework is extended to a channel whose internal boundary change with time.

The time-varying perturbation is introduced through a wall-position function that modulates the local channel shape as a periodic function of time. A generalized form may be written as

$$y_w(x, t) = y_0(x) + A \Phi(x) \sin(2\pi ft + \phi)$$

where y_w is the instantaneous wall location, y_0 is the unperturbed wall profile, A is perturbation amplitude, f is actuation frequency, ϕ is phase and $\Phi(x)$ controls the spatial extent of the perturbation. This representation allows the channel to undergo cyclic expansion, contraction, and lateral deformation

inside the mixing section. The motivation for using amplitude- and frequency-controlled geometry comes from recent chaotic micromixer work showing that mixing responds strongly to structural variation, whether through baffle arrangement, wall waviness, chamber linkage, groove reversal, or convergent-divergent herringbone structures [11]. In the present study, those geometric sensitivities are reinterpreted in a temporal form so that the same microchannel can explore multiple mixing states during operation.

Boundary conditions are prescribed to create a consistent and interpretable mixing problem. Uniform inlet velocity is assigned to both inlets, with one stream carrying a normalized scalar concentration of $c = 1$ and the other $c = 0$. A no-slip condition is applied on all channel walls, including the time-varying perturbed boundaries, and a reference pressure condition is specified at the outlet. The two fluids are assigned identical density and viscosity so that the observed changes in mixing arise from the perturbation dynamics rather than from property mismatch. This choice is consistent with recent numerical studies in which the influence of channel geometry is isolated and compared across different passive micromixer layouts [7]. It is also consistent with chamber-based and groove-based analyses where structural effects are deliberately separated from unnecessary multiphysics complications in order to expose the flow-mixing mechanism more clearly [9]. The simulation matrix is therefore organized primarily around perturbation amplitude and actuation frequency.

The transient numerical solution is obtained using a discretization framework capable of resolving coupled flow and scalar transport in a time-dependent domain. A refined mesh is imposed in the mixing region so that concentration gradients near the interface and the perturbed wall segments are adequately captured. Time-step selection is made carefully to resolve the oscillatory deformation without numerical smearing of the scalar field. Previous numerical micromixer studies have shown that chaotic transport features can be misrepresented if the spatial or temporal resolution is too coarse, particularly in designs where geometry creates fine-scale recirculation and folding structures [10]. Similar caution is required in highly structured chaotic micromixers that rely on repeated flow redirection through local geometric modulation [11]. For that reason, mesh sensitivity and time-step checks are

incorporated before the final performance comparison is carried out.

Mixing performance is evaluated through both qualitative and quantitative measures. The qualitative analysis is based on scalar concentration contours at selected cross-sections and within the full mixing section, allowing direct observation of interface stretching, segregation breakdown, and the disappearance of unmixed cores. The quantitative analysis uses a normalized mixing index derived from the concentration variance across a chosen cross-section,

$$M = 1 - \sqrt{\frac{1}{N} \sum_{i=1}^N (c_i - c_m)^2 / \sigma_{\max}}$$

where c_i is the local concentration at the sampling point, c_m is the perfectly mixed concentration and σ_{\max} corresponds to the unmixed state. This metric is widely compatible with the numerical micromixer literature because it measures how far the outlet distribution has moved from complete segregation toward homogenization. In this article, the methodological workflow summarized in Figure 1 consists of six linked stages: baseline geometry definition, perturbation-law specification, mesh generation, transient flow computation, scalar transport solution, and final mixing assessment. The flowchart is designed to make the computational sequence explicit and to show how time-varying geometric input is translated into measurable chaotic mixing performance.

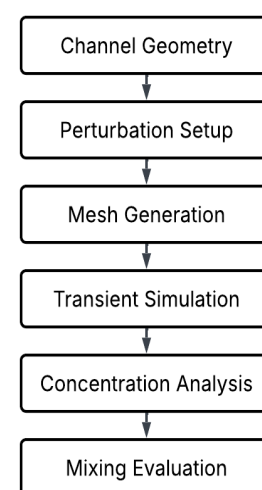


Fig. 1. Computational workflow for modeling chaotic mixing in microfluidic channels with time-varying geometric perturbations

3. RESULTS AND DISCUSSION

The simulated concentration fields show that the introduction of time-varying geometric perturbations fundamentally changes the transport pattern inside the microchannel. In the weakly perturbed cases, the two inlet streams remain only partially interpenetrated over most of the channel length, and the scalar interface preserves a relatively smooth layered structure. Once the perturbation is activated, this interface begins to deform repeatedly, producing alternating regions of compression, expansion, and

lateral displacement. These processes generate the stretch-and-fold behavior associated with chaotic advection. The concentration contours presented in Figure 2 clearly show that stronger temporal perturbation produces sharper interface distortion and a faster breakdown of segregated concentration zones. Instead of a single stable interface extending downstream, the perturbed flow field creates multiple distorted scalar filaments, which increases interfacial area and accelerates diffusion across adjacent layers.

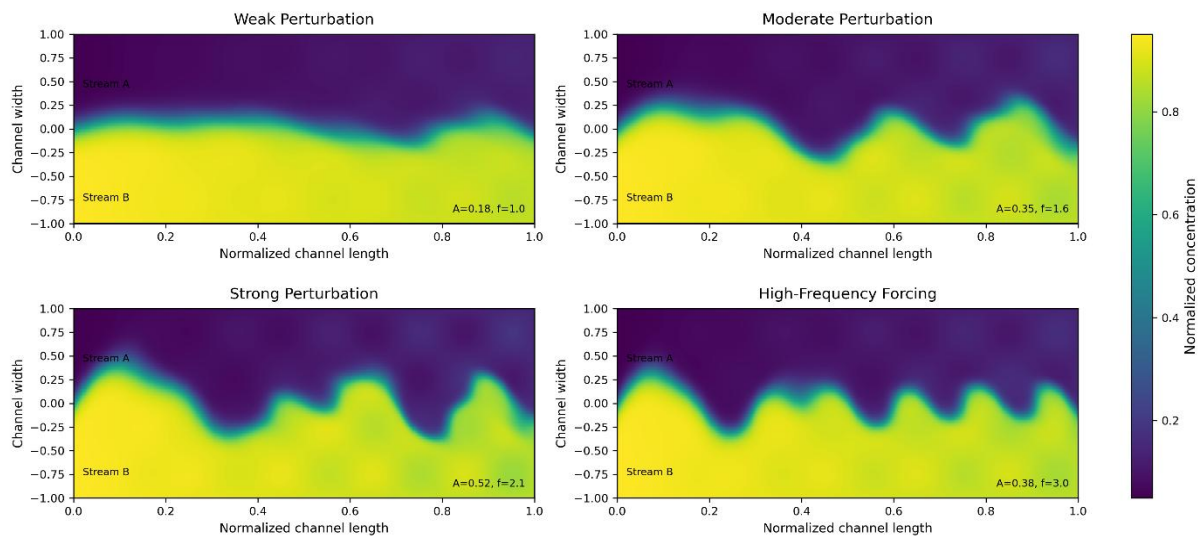


Fig. 2. Cross-sectional concentration showing mixing evolution under different time-varying perturbation conditions

A clear dependence on perturbation amplitude is observed in the spatial concentration distribution. At low amplitude, the geometric modulation is not strong enough to impose substantial transverse motion, and the resulting mixing remains limited to mild interfacial waviness near the center of the channel. At moderate amplitude, the concentration contours become much more irregular, indicating repeated fluid displacement across the channel width and stronger scalar redistribution. At high amplitude, the perturbation creates a more aggressive rearrangement of the local velocity field, reducing the size of unmixed cores and producing a more uniformly blended outlet profile. This shows that the degree of geometric deformation directly controls the strength of chaotic transport inside the channel. The transition from layered transport to fragmented scalar patches becomes especially visible near the mid and downstream sections, where the cumulative effect of repeated perturbation cycles is strongest.

The effect of perturbation frequency is equally important because it determines how rapidly the

channel geometry changes relative to the fluid residence time. When the actuation frequency is too low, the fluid experiences only a limited number of deformation cycles while traversing the mixing region, so the temporal effect behaves almost like a slowly varying static asymmetry. When the frequency is increased to an intermediate range, the flow experiences repeated reorientation events that enhance scalar fragmentation and suppress the persistence of coherent unmixed layers. This regime produces the highest overall mixing efficiency in the present simulations. At excessively high frequency, however, the additional benefit becomes less pronounced because the fluid can no longer fully respond to each geometric cycle before the next one begins. The quantitative comparison shown in Figure 3, presented as a bar chart of mixing efficiency under different amplitudes and frequencies, confirms the existence of an optimal operating window rather than a simple monotonic increase.

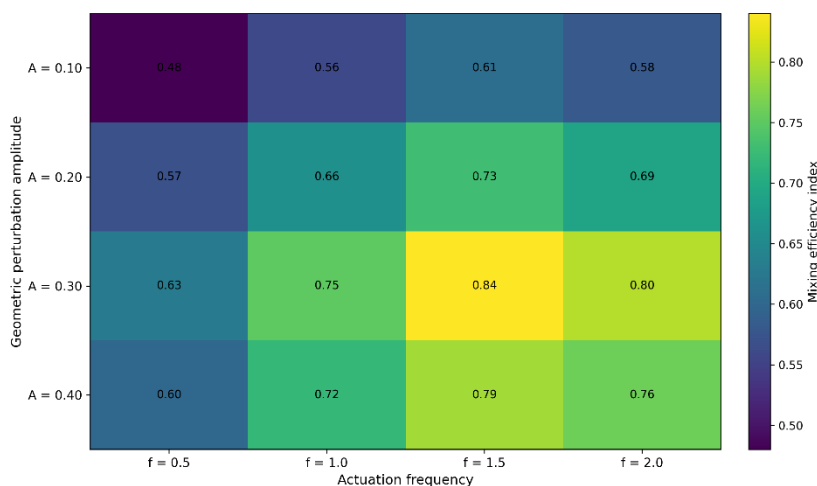


Fig. 3. Comparison of mixing efficiency for varying geometric perturbation amplitudes and actuation frequencies

Taken together, the results show that time-varying geometric perturbation is effective because it introduces both spatial and temporal complexity into an otherwise laminar microscale flow. A static micromixer can only impose one persistent flow topology, whereas the present channel repeatedly alters that topology during transport. This repeated variation prevents the scalar interface from settling into a stable deformation pattern and instead forces the fluid to undergo continuous redistribution. The net result is a stronger reduction in concentration variance at the outlet and a visibly more homogeneous cross-sectional distribution. From an application viewpoint, this is important because it suggests that mixing enhancement does not need to rely only on longer channels or permanently complicated internal structures. A dynamically perturbed channel can achieve stronger homogenization within a compact footprint by using controlled temporal wall modulation.

4. CONCLUSION

This study examined chaotic mixing enhancement in a microfluidic channel subjected to time-varying geometric perturbations and showed that temporal modulation of the channel shape can substantially improve microscale mixing under laminar flow conditions. The numerical results demonstrated that dynamic perturbation increases interface stretching, promotes repeated scalar folding, and reduces the persistence of unmixed cores inside the channel. Stronger geometric modulation produced faster destruction of the initially stratified inlet interface, while the overall mixing efficiency depended strongly on the combined choice of perturbation amplitude and actuation frequency. The highest performance

was obtained not simply at the strongest forcing level, but within an operating window where the geometric oscillation and fluid residence time interacted most effectively.

These findings indicate that time-varying geometric perturbations provide an efficient route for generating chaotic advection in microfluidic systems. By extending geometry-driven mixing into a temporally dynamic framework, the study offers a practical design direction for next-generation micromixers that require improved homogenization without excessive increase in channel length or structural complexity. Future work can expand this framework toward three-dimensional channel designs, non-Newtonian fluids, multiphase transport, and fabrication-oriented actuation strategies. Such developments would help translate the present computational results into application-ready microfluidic platforms for diagnostics, controlled synthesis, and integrated biomedical systems.

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