



## RESEARCH ARTICLE

## OPEN ACCESS

# FLOW-BASED MIXING OF NON-NEWTONIAN FLUIDS IN TLCCM PASSIVE MICROMIXERS: A COMPARATIVE PERFORMANCE STUDY

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## ABSTRACT

High-efficiency micromixers are crucial in industrial applications. Passive chaotic advection effectively enhances fluid mixing by generating strong secondary flows that help homogenization microscopically. The aim of the present study is to compare different configurations of passive two-layer cross-channel micromixers of various shapes: (TLCCM 1), (TLCCM 2), and (TLCCM 3). The micromixers considered in this study have the same hydraulic diameter and the same equivalent unfolded length of 7.5 mm. Numerical simulations were performed using the Fluent CFD code to solve the momentum equations, the continuity equation, and the species transport equation. The non-Newtonian fluids employed are carboxymethyl cellulose solutions, which are modeled by power-law model with a flow behavior index ranging from 0.49 to 1, and the generalized Reynolds number varies between 1 and 50. Mixing efficiency was evaluated by calculating the mixing degree at different cross-sections. To examine the results obtained through numerical simulations, the mass fraction distributions, pressure losses, and mixing energy costs were presented. The results show that this type of TLCCM micromixer exhibits a high mixing degree, exceeding 0.857 for all values of the generalized Reynolds number and the considered flow behavior index, and it displays relatively low mixing energy costs, particularly for Newtonian fluids.



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## I. INTRODUCTION

Passive micromixers are microfluidic devices designed to mix fluids through micrometer-scale channels. These operate mainly based on the internal geometry of the channels, which alters the flow path, induces secondary flows, and increases the interfacial contact area between fluid streams [1]. Owing to their simple structure, easy fabrication, low cost, and low energy consumption, these mixers have, in fact, become one of the most widely used microfluidic devices [2-6]. Due to their high stability and ease of integration with complex microfluidic units, they are positioned as the primary elements in lab-on-a-chip devices and microanalytical systems [5-8]. Mixing usually is a process to reduce concentration and temperature gradients by means of momentum, mass, or heat transfer through turbulence or chaotic laminar advection [6-8]. Nevertheless, the generation of turbulence in very viscous or highly sensitive fluids, for instance, non-Newtonian ones, is frequently a process that consumes a lot of energy and can cause the breaking of their structure [9]. In these instances, chaotic advection mixing provides a superior option. Consequently, researchers are motivated to develop micromixers that function under chaotic advection, chiefly for non-Newtonian fluids, which are less investigated compared to the numerous studies on Newtonian fluid mixing [10] [11]. Within this framework, [12] illustrate that curved micromixers significantly improve the mixing of shear-thinning fluids, particularly at smaller curvature radii and higher Reynolds numbers. In their subsequent work, they show that 30° bottom-wall grooves enhance the strength of chaotic perturbations without increasing the pressure drop, thereby improving mixing across all flow indices tested [13]. In line with these results, [14] study an alternating current (AC) electrothermal micromixer and report that mixing uniformity improves with increasing power-law index, with shear-thickening fluids benefiting most from electrothermal-geometric interactions.

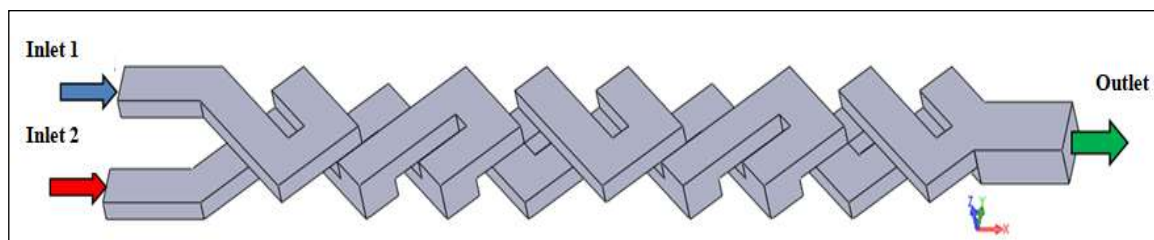
Conversely, [15] find that dilatant fluids exhibit strong diffusion-regime mixing at low Reynolds numbers, whereas pseudoplastic fluids perform well over a wider Re range. With their comparative study of six 3D split-and-recombine micromixers, He et al. [16] recognize the Double-Bridge E-Shape Micromixer (DBEM-3) arrangement as the one resulting in more than 95% mixing efficiency for Newtonian and pseudoplastic fluids and thus provide further insight into the influence of geometry. The work of Lobasov et al. [17] goes a long way in clarifying the non-Newtonian effects in T-shaped micromixers. Their experiments show that mixing is very much a function of viscosity, density, and temperature, and that a higher flow behavior index helps mixing only up to a point when symmetric inflow conditions are present, while it becomes almost inactive in asymmetric configurations. The findings, therefore, emphasize that inlet conditions govern not only vortex formation but also streamwise stretching. Different studies have also looked at new geometries and mixing methods. Bayareh et al. [18] employ the Carreau–Yasuda model to study the behavior of shear-thinning fluids around an eccentric cylindrical obstacle and report a mixing index of 63.7%, compared with 33.1% for Newtonian fluids. They also observe that the pressure drop reduces at higher velocities and that diffusion effects are still very minor. [19] simulate a 3D Y-shaped micromixer and demonstrate that lower flow rates provide better mixing and that the higher viscosity of ethanol leads to a mixing index of 100% at  $Q_v = 0.1 \mu\text{L}/\text{min}$ , while it is only 80% for water. Peixoto et al. [20] carry out an experimental study of seven T-shaped micromixers with different obstacle shapes and state that multiple obstacles improve mixing at  $Re = 40\text{--}200$  for symmetric inlets but can lower the performance at  $Re > 119$  for asymmetric conditions. Juraeva et al. [21] develop a straight multi-passage micromixer and conclude that two converging passages are ideal for mixing due to the extended fluid interfaces and intense secondary flows, especially at low and intermediate Reynolds numbers. In this respect, Ghanbari et al. [22] further investigate different methods and make a systematic comparison of triangular, rectangular, trapezoidal, and circular T-mixers to demonstrate that different geometries exhibit different performance, and triangular designs achieve the best mixing, 8.3% higher than that of circular mixers.

This is because the insertion of the obstacles causes a 34% increase in mixing at higher Re due to intensified vortex generation. In recent years, the Two-Layer Crossing Channels Micromixer (TLCCM) has been the focus of attention for the outstanding performance that the device exhibits in the mixing of both Newtonian and non-Newtonian fluids. Initially, Kouadri et al. [23] [24] show that shear-thinning fluids can reach very high mixing indices (>85–99%) even at very low Reynolds numbers, and the best geometries ( $l/W = 1$ ) reduce pressure losses. In later comparisons with different configurations such as L-Shape, OH, OX, Semicircular Serpentine Micromixer (SCSM-90), Curved micromixer with Grooves (CG), and C-Shape micromixers, Kouadri et al. [25] and Douroum et al. [26] show that TLCCM is still the most effective in creating powerful secondary flows that result in very high hydrodynamic and thermal mixing efficiencies (mixing index (MI) up to 0.99, thermal MI > 0.932) at almost the same energy levels. Douroum et al. [26] emphasize the major role that flow kinematic parameters - helicity, rotation, and vortex intensity - have in raising these secondary flows, which in turn leads to the enhancement of homogenization for shear-thinning fluids over a broad range of Reynolds numbers. Recent studies by Kouadri et al. [9], Douroum et al. [27], and Zaitri et al. [28] deepen our understanding of TLCCM and its optimized variants (e.g., TLCCM-O) as very efficient for pseudoplastic fluids, achieving high hydrodynamic and thermal mixing (MI = 0.805–0.998, thermal MI = 0.9–0.99), nearly isothermal temperature distributions, very low entropy generation, and low energy consumption. Overall, these studies emphasize the unique ability of TLCCM to perform efficient mixing of non-Newtonian fluids in laminar microfluidic flows, which in turn serves as a strong basis for our present work, which examines three types of two-layer crossing channels micromixers that offer excellent mixing performance with low mixing energy costs. The mixing performance is investigated using the three-dimensional Navier–Stokes equations over a Reynolds number range of 1 to 50. The effect of the flow behavior index on non-Newtonian fluids is studied, and the obtained results for the mixing degree, pressure losses, and mixing energy costs are then compared.

## II. MATHEMATICAL AND NUMERICAL MODELING

### II.1 EMPLOYED GEOMETRICAL MODELS

The micromixers considered in this research work are based on the configuration suggested by Xia et al [29]. A schematic illustration of the micromixer is given in Figure 1. It is composed of two twisted microchannel configurations with the same geometrical dimensions. The upper and lower configurations are periodically arranged such that there is a maximum interaction between the two layers through the connected regions. For the reference configuration of the micromixer, the important geometrical dimensions considered are as follows: overall micromixer width ( $H$ ) = 1.07 mm, channel width ( $w$ ) = 0.30 mm, channel height ( $b$ ) = 0.15 mm, distance between transverse channels ( $p$ ) = 0.64 mm, diagonal channel height ( $d$ ) = 0.15 mm, and the number of mixing units = 9. Dimensions of the cross-sectional areas at the outlet and the inlet are  $0.15 \times 0.30 \text{ mm}^2$  and  $0.30 \times 0.30 \text{ mm}^2$ , respectively.



TLCCM 1.

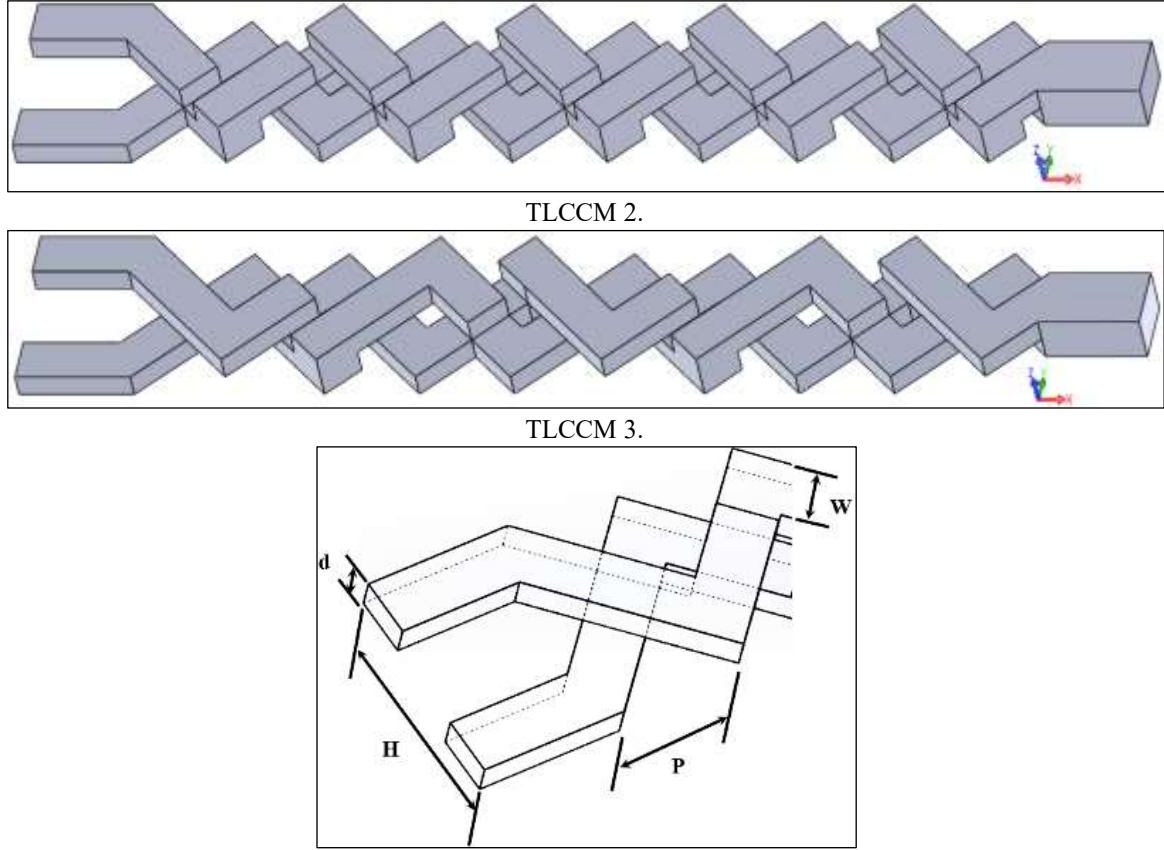


Figure 1: Schematic diagrams of the considered micromixers.  
Source: Authors, (2026).

## II.2 GOVERNING EQUATIONS

The governing equations are the continuity equation (1), the momentum equation (2) that includes the shear stress tensor, and the species transport equation (3), where the fluid is assumed to have constant density and viscosity. The flow is assumed to be steady and incompressible. The governing equations can be written as follows:

$$\nabla \cdot \vec{U} = 0 \quad (1)$$

$$\rho \vec{U} \cdot \nabla \vec{U} = -\nabla P + \bar{\tau} \quad (2)$$

$$\vec{U} \cdot \nabla C = D \nabla^2 C \quad (3)$$

In this regard,  $U$ ,  $\rho$ ,  $P$ ,  $\bar{\tau}$ ,  $D$ , and  $C$  refer to the fluid velocity, fluid density, static pressure, shear stress tensor, molecular diffusion coefficient, and species concentration, respectively. The stress tensor is given by:

$$\bar{\tau} = \eta \bar{\dot{\gamma}} \quad (4)$$

Where,  $\bar{\dot{\gamma}}$  is the shear rate tensor.

$$\bar{\dot{\gamma}} = \nabla \vec{U} + \nabla \vec{U}^T \quad (5)$$

The exponent T denotes the transpose operator. The apparent viscosity (6) is described by the Ostwald–de Waele power-law model [30], as follows:

$$\eta = m \dot{\gamma}^{n-1} \quad (6)$$

$$\dot{\gamma} = \sqrt{1/2(\bar{\dot{\gamma}} : \bar{\dot{\gamma}})} \quad (7)$$

Where  $m$ , and  $n$  represent the consistency index and the flow behavior index, respectively. The governing equations are solved numerically by applying a no-slip boundary condition at the channel walls and imposing uniform velocity profiles at the inlets. Atmospheric pressure is specified as the outlet boundary condition. In this study, the Semi-Implicit Method for Pressure-Linked Equations-Consistent (SIMPLEC) algorithm was employed for pressure–velocity coupling. A second-order upwind scheme was used to discretize the convective terms in both the momentum and species transport equations. For improved accuracy, the governing equations were solved iteratively until the relative residuals of all variables fell below  $10^{-6}$ . The expression for the generalized Reynolds number ( $Re_g$ ) given by Delplace et al. [30], for a power-law fluid flowing through rectangular sections, is defined as:

$$Re_g = \frac{\rho U_m^{2-n} D_h^n}{m \left[ \frac{24n + \xi}{(24 + \xi)n} \right]^n \xi^{n-1}} \quad (8)$$

With  $U_m$  being the mean flow velocity, and for a rectangular conduit, the geometric parameter  $\xi = 7.774$ . The working fluid is the Carboxymethyl Cellulose (CMC) solution, which is considered a non-Newtonian fluid,  $\rho = 1000 \text{ kg/m}^3$ ,  $D = 3.6 \times 10^{-10} \text{ m}^2/\text{s}$ . The degree of mixing  $D_m$  is an important parameter for quantifying the mixing, which can be calculated in each section of the micromixer as follows:

$$D_m = 1 - \frac{\sigma}{\sigma_0} \quad (9)$$

Where  $\sigma$  is the standard deviation of the mass fraction in a cross-sectional area:

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (c_i - \bar{c})^2 \quad (10)$$

Here,  $N$  is the total number of cells in a section,  $c_i$  is the mass fraction in the considered section, and  $\bar{c}$  is the mean of  $c_i$ .

$$\sigma_0^2 = \bar{c}(1 - \bar{c}) \quad (11)$$

### II.3 MESH SENSITIVITY ANALYSIS

Numerical simulations were performed for the TLCCM 1 micromixer with different mesh densities as shown in Figure 2 to assess the effect of mesh refinement on the predicted mixing level. Based on the results obtained for the mesh independence study, the mesh with 1,217,668 elements is used for the present study.

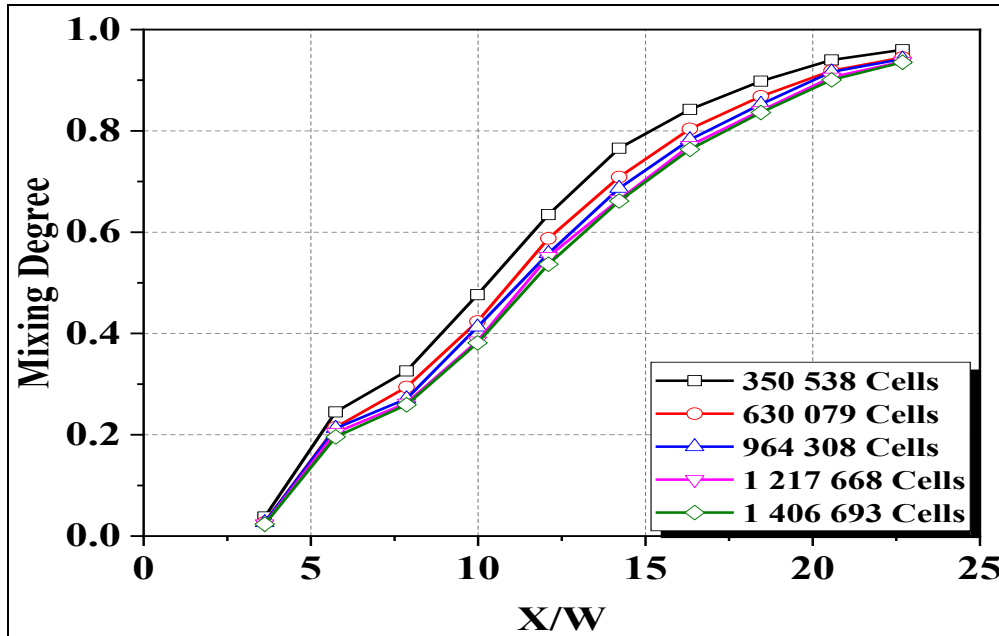


Figure 2: Mesh sensitivity analysis for the TLCCM 1 geometry ( $Re_g = 50$  ;  $n = 0.49$ ).  
Source: Authors, (2026).

## III. RESULTS AND DISCUSSION

### III.1 CFD CODE VALIDATION

The results of the numerical simulation are quantitatively and qualitatively compared with previously reported results (Xia et al [29]), as shown in Figure3. In Figure3 (a), the mass fraction distributions of the y-z planes along the micromixer with  $Re = 0.2$  are shown. In Figure3 (b), the x-y planes represent the meridional planes in the upper and lower channels. From a quantitative point of view, the change in standard deviation is in good agreement with the previously reported results.

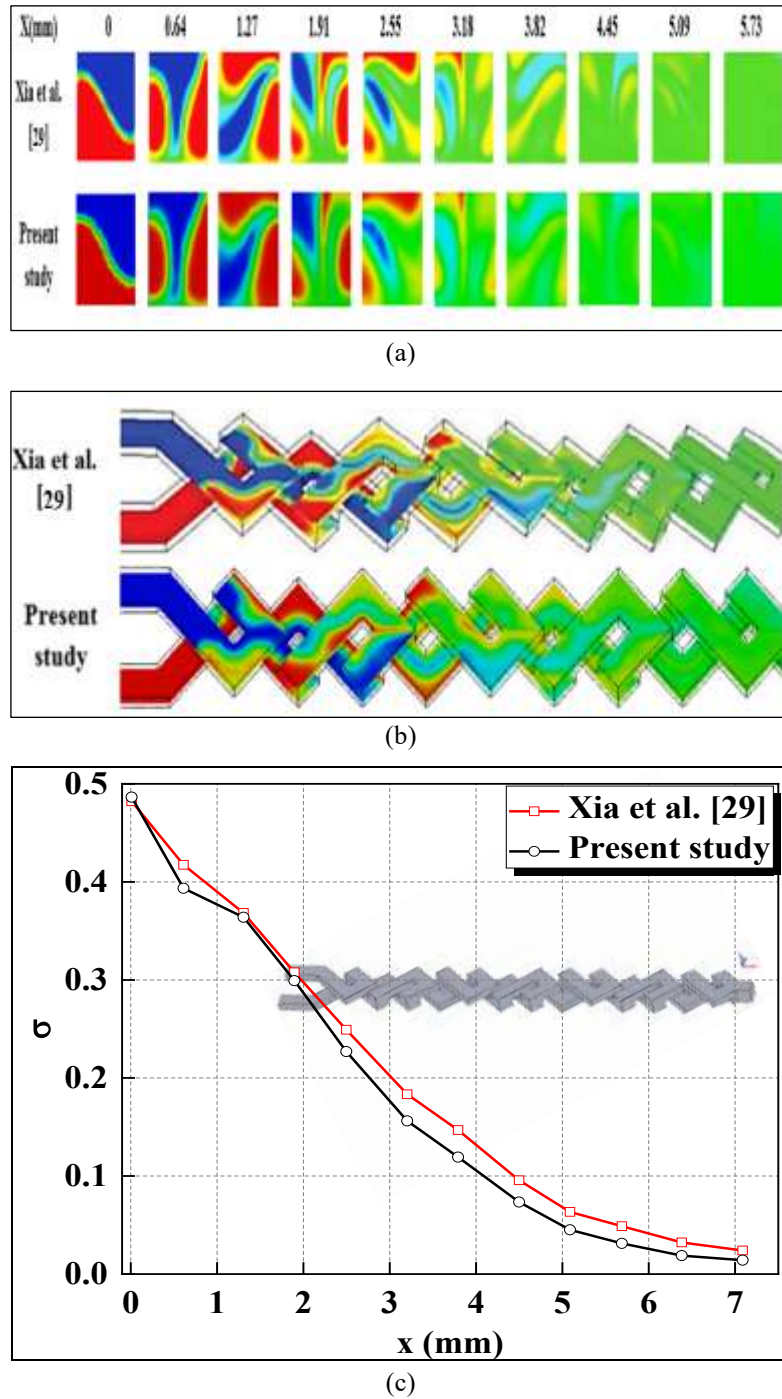


Figure 3: Qualitative and quantitative validation against previously published results ( $Re = 0.2$ ): (a) Mass fraction contours in different cross-sections; (b) Mass fraction contours in the meridional plane of the micromixer; (c) Evolution of the standard deviation along the micromixer.

Source: Authors, (2026).

### III.2 HYDRODYNAMIC MIXING PERFORMANCE

To demonstrate the mixing performance of the TLCCM micromixers, it is relevant to examine the variation of the degree of mixing at the outlet section of the considered configurations. As shown in Figure 4, the degree of mixing exceeds 0.86 for all micromixers, regardless of the value of the generalized Reynolds number and for all considered values of the flow behavior index ( $n$ ). This demonstrates the high mixing performance achieved using this type of micromixer, particularly at low Reynolds numbers, which is due to the nature of the TLCCM geometry that allows the division and recombination of the flows coming from the top and bottom layers, generating in each cross-sectional area of the junction the stretching and compression of fluid filaments along the diagonals. It is also noted that the TLCCM 2 geometry exhibits better mixing performance across the entire range of the generalized Reynolds number and all flow behavior indices ( $n$ ).

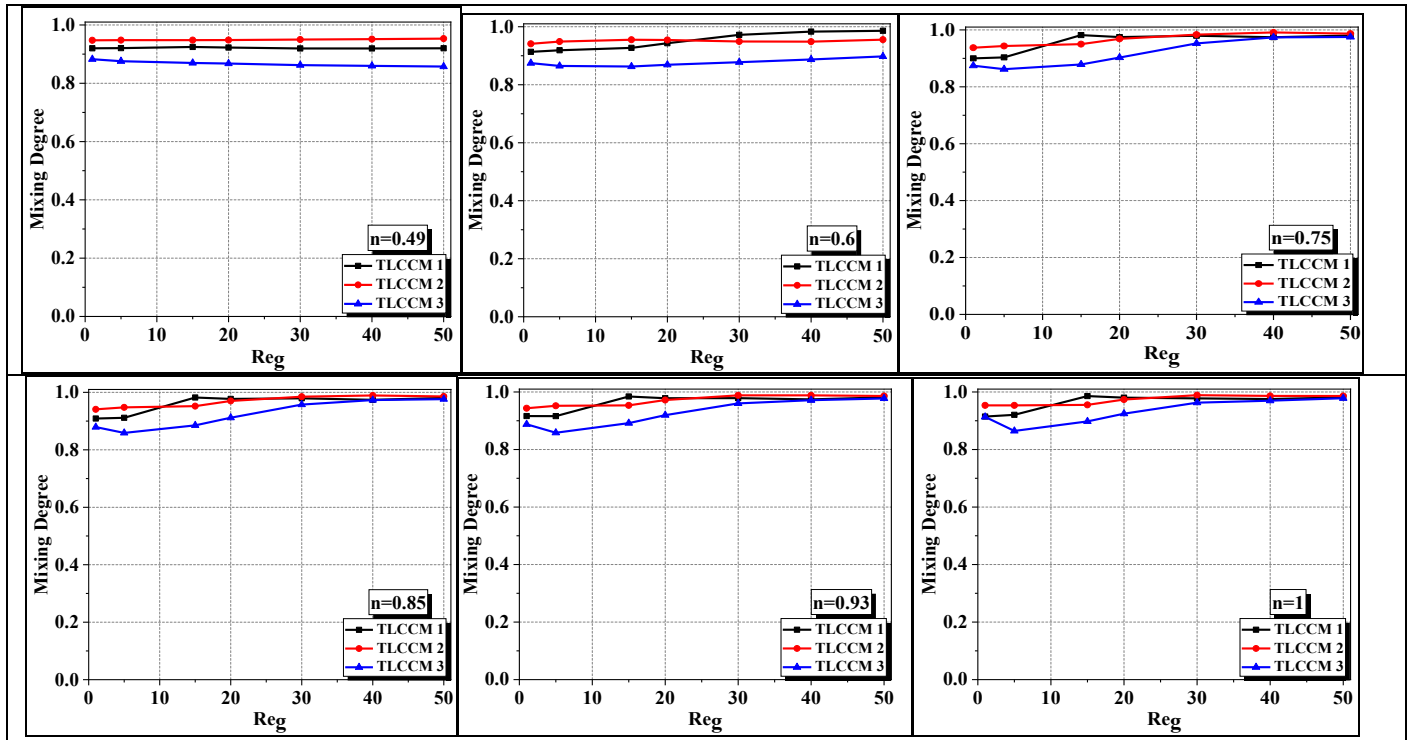


Figure 4: Variation of the degree of mixing as a function of  $Re_g$  for different flow behavior indices  $n$ .  
Source: Authors, (2026).

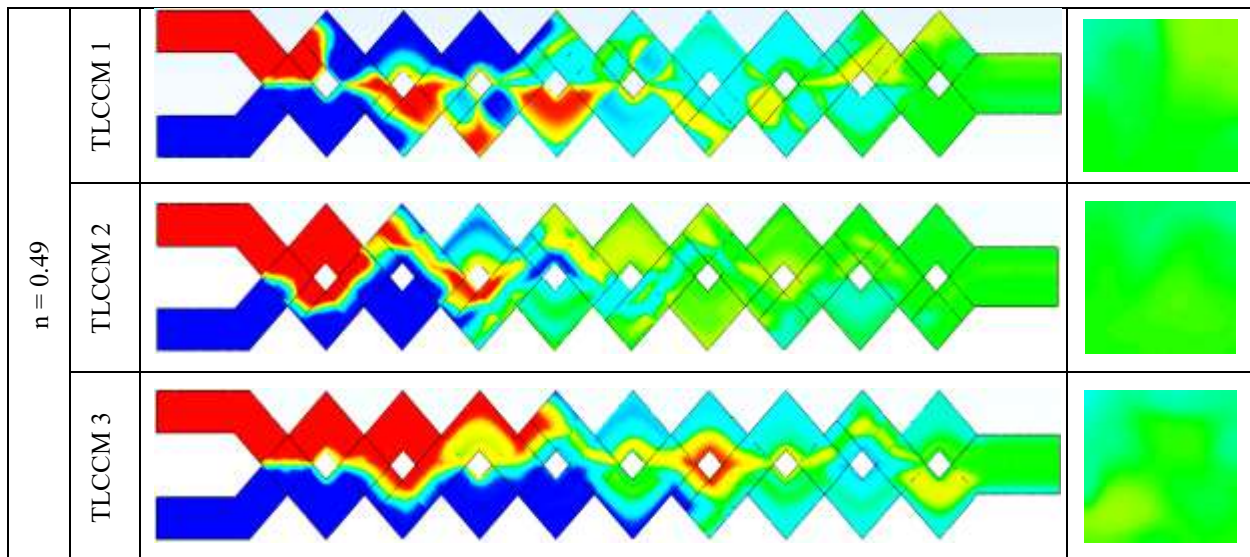
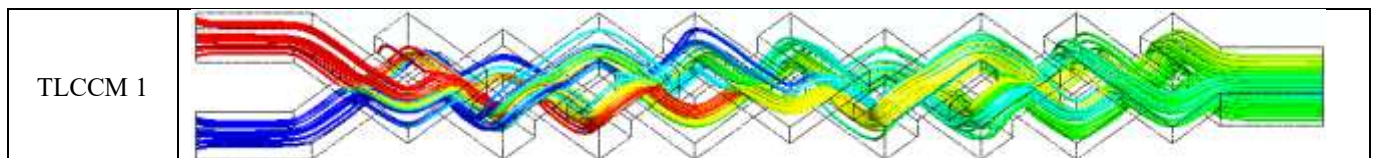


Figure 5: Comparison of the mass fraction contours in the meridional plane of the considered micromixers for  $Re_g = 1$ ;  $n = 0.49$ .  
Source: Authors, (2026).

Figure 5 shows the mass fraction distribution contours in the meridional plane and at the outlet section of the different micromixers for  $Re_g = 1$  et  $n = 0.49$ . It is clearly observed that all micromixers exhibit high mixing performance, leading to a nearly homogeneous mixture at the outlet plane. Furthermore, from the meridional plane contours, it can be noted that a homogeneous mixture is achieved starting from the fifth intersection in the TLCCM 2 micromixer. The flow structure is illustrated using streamlines, as shown in Figure 6 for  $Re_g = 1$  et  $n = 0.49$ , in the TLCCM 1, TLCCM 2, and TLCCM 3 micromixers. The streamlines are interconnected at the intersections. A portion of the fluid originating from the upper-layer channel enters the lower-layer channel. This is clearly evidenced by the appearance of streamlines with different colors downstream of each intersection node, indicating stretching and compression of the fluid streams. It is noteworthy that the TLCCM micromixer structure promotes the entanglement of streamlines at the intersection nodes, thereby enhancing mixing through chaotic advection.



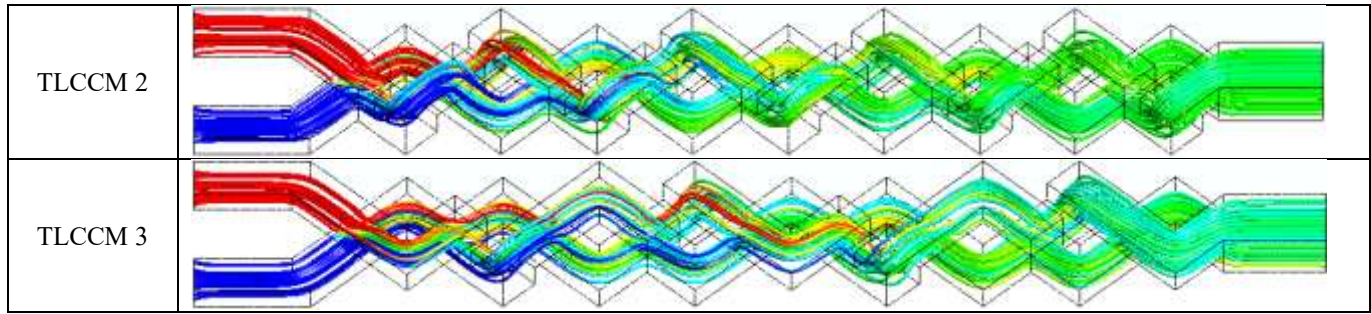


Figure 6: Streamlines colored by mass fraction in the considered micromixers for  $Re_g = 1$  et  $n = 0.49$ .  
Source: Authors, (2026).

### III.3 PRESSURE LOSSES AND MIXING ENERGY COSTS

The pressure drop must be considered together with the degree of mixing and the flow rate when evaluating the overall performance and reliability of micromixers. Therefore, it is important to introduce the mixing energy cost (MEC), which is defined as follows:

$$MEC = \frac{Q \times \Delta P}{D_m} \quad (12)$$

Where  $Q$  is the volumetric flow rate of the fluid ( $m^3/s$ ), and  $\Delta P$  denotes the pressure drop along the micromixer. For the selection of a micromixer that provides the best mixing performance with the lowest mixing energy cost, Figure 7 presents a comparison of the mixing energy costs for the proposed micromixers over a range of generalized Reynolds numbers from 1 to 50. It can be observed that at low generalized Reynolds numbers, all micromixers exhibit relatively low mixing energy costs. Moreover, the mixing energy cost is extremely low, on the order of micrometers, for Newtonian fluids, and it remains generally low for non-Newtonian fluids as well.

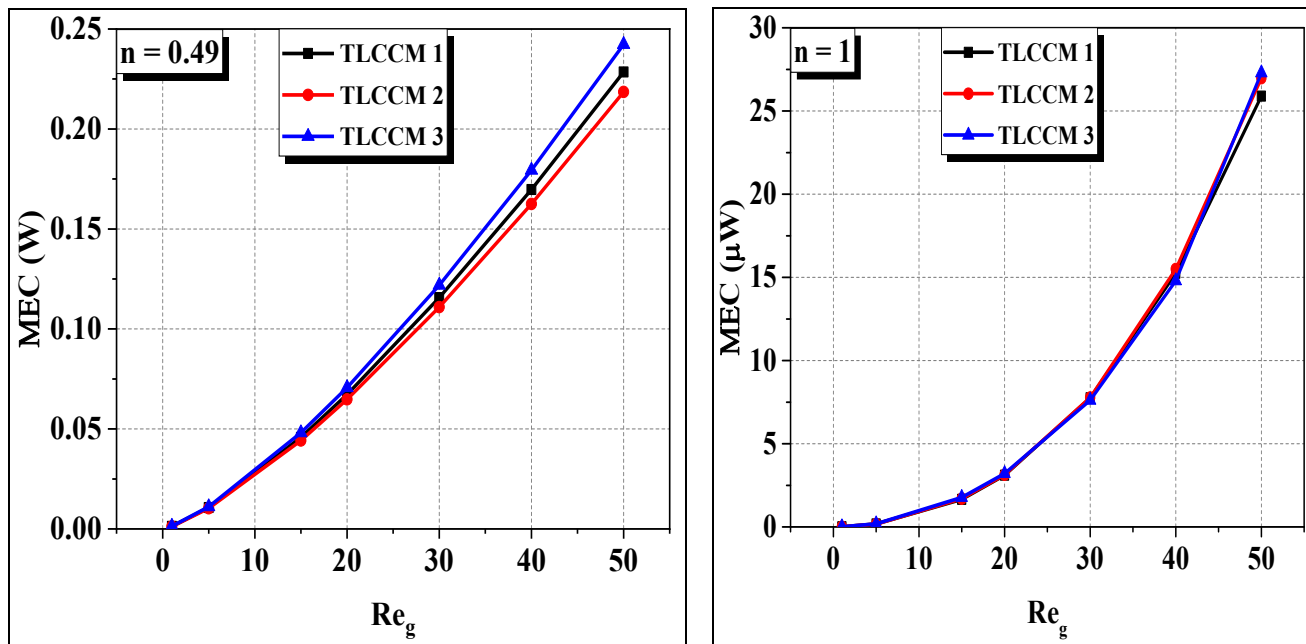


Figure 7: Comparison of the mixing energy cost in the considered micromixers for  $n = 0.49$  et  $n = 1$ .  
Source: Authors, (2026).

### IV. CONCLUSIONS

A detailed numerical study of hydrodynamic mixing performance was conducted using the degree of mixing and qualitative mass fraction distributions. The hydrodynamic and rheological behaviors were analyzed based on secondary flow structures and mixing energy costs across the proposed micromixers. The results demonstrate that the TLCCM 2 micromixer achieves the best mixing performance, with a degree of mixing exceeding 0.86 and reaching up to 0.988 across all generalized Reynolds number values and flow behavior indices. Mass fraction distributions in the meridional planes and at the outlet confirmed the clear superiority of TLCCM 2 over TLCCM 1 and TLCCM 3. Furthermore, streamline visualization revealed the secondary flow structures and their influence on mixing efficiency. Notably, the TLCCM 2 micromixer exhibits relatively low mixing energy costs, particularly at low Reynolds numbers, confirming its energy efficiency. Therefore, the TLCCM 2 micromixer represents the optimal design for achieving effective hydrodynamic mixing at minimal energy cost.

## V. AUTHOR'S CONTRIBUTION

**Conceptualization:** Belakhal Djemaa, Kouadri Amar and Douroum Embarek.

**Methodology:** Belakhal Djemaa, Kouadri Amar and Douroum Embarek.

**Investigation:** Belakhal Djemaa, Kouadri Amar and Douroum Embarek.

**Discussion of results:** Kouadri Amar, Belakhal Djemaa and Douroum Embarek.

**Writing – Original Draft:** Belakhal Djemaa, Kouadri Amar and Douroum Embarek.

**Writing – Review and Editing:** Kouadri Amar, Belakhal Djemaa and Douroum Embarek.

**Resources:** Belakhal Djemaa, Kouadri Amar and Douroum Embarek.

**Supervision:** Kouadri Amar, Belakhal Djemaa and Douroum Embarek.

**Approval of the final text:** Belakhal Djemaa, Kouadri Amar and Douroum Embarek.

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