Micro T-mixer with variable inlet widths: Experimental characterization of Newtonian fluid mixing using time pulsing

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Abstract

Unlike that occurring at the macroscopic scale, the different physical phenomena supporting most microfluidic applications, which operate under laminar flow, make the mixing process one of the most important challenges, in this area. T-micromixers with different widths in the inlet channels are used to evaluate the mixing capacity, when a pulsed signal is imposed on the input flows. The manufacture of microchannels was developed using polydimethylsiloxane, based on soft lithography techniques. In turn, the images of the experiments were acquired with a high resolution and high frequency camera, coupled to a microscope, and then digitally processed. For both the symmetrical and asymmetrical geometries, the mixture quality was characterized, depending on the $Re$, for continuous flows, showing that the $Re$ is the fundamental parameter influencing the mixers performance. For pulsed flows, the analysis was based on the parameters that characterize the pulsed signal imposed on one or both micromixer inlet channels. Results showed, that as far as the phase difference is concerned, the application to both inputs in phase opposition is the most beneficial, while for amplitude, similarly to the continuous case, the mixing quality increases with the average flow rate, and an increase in frequency results in a decrease of the mixing quality. Moreover, an additional study was made for the influence of the geometrical parameters that define the mixing channel, analysing different sections at the outlet channel and also the variation of the channel width, verifying that narrower and longer mixing channel are the beneficial to the mixing quality.

Keywords: Microfluidic, T-micromixer, Pulsed flow, Mixing, Microfabrication

1. Introduction

Over the last decade, the use of microfluidic devices has been widely investigated, as these hold the promise for the automation of a wide range of Chemical and Biological areas, such as disease diagnosis or drug delivery [1], suggesting the possibility of carrying out numerous experiments, quickly and in parallel, through the reduced consumption of reagent [2, 3]. However, the deterministic nature of laminar flow, patent of most microfluidic applications, such as microfluidic Lab-on-chip (LOC) and micro-total-analysis-systems ($\mu$TAS), due to the high ratio between the surface area and volume, which makes transition to turbulent flow extremely difficult to achieve [1, 4], when compared to its macroscopic counterpart, has established the lengthy mixing process as one of the main challenges to overcome for accomplishing success and the widespread use of such systems [5].

Micromixers can be classified as active, where the mixing process is improved by the use of external energy sources, which induce vorticity to the flow and alter the conveyance of the diffusive process, or passive, when the mixing process is only promoted through the channel geometry [1, 4, 6]. The present work refers to the second case, mostly due to its manufacturing simplicity, robustness and easy integration, and the fact that efficient mixing has been demonstrated to be achievable [1, 4, 6].

One of the most studied passive micromixer configurations consists of a T-shaped geometry, where two symmetrical and opposing streams enter simultaneously through the inlets and are joined at the junction, occurring the mixing process throughout the outlet, perpendicular to the inlets, and hereafter referred to as mixing channel. According to several studies [7, 8, 6], three different laminar flow regimes have been identified, for symmetrical T-micromixers: (i) For lower $Re$ molecular diffusion is the main transport phenomena for bulk motion of particles, as both flows remain segregated; (ii) for medium $Re$, due to instabilities caused by the centrifugal force, which influences the flow around the dihedral, secondary fluid transport in the transverse direction occurs, in the form of a pair of vortices. However, the flow in the mixing channel stills
presents itself as symmetrical, with respect to the plane perpendicular to the entrances, and no disruption of the fluids interface occurs. Mixing quality is improved by the vortex perturbation, but it still remains low, as diffusion still remains the dominant transport phenomena; (iii) for higher \( Re \), the greater weight of the instabilities caused by the channel geometry results in the disruption of the interface between the fluids, in the mixing channel. With the onset of this so called engulfment regime, and the consequent collapse of the symmetrical characteristics of the previous two regimes, the streamline become entangled, greatly improving the mixing quality by mass advection [9, 7, 8], and thus the performance of the T-micromixer. Improvements in mixing intensity should therefore be expected for asymmetric mixing schemes. The range of \( Re \) for which these regimes occur seems to be dependent on the microchannel geometry, particularly on the relation between the channel width and the height [10, 11, 7, 8].

As the onset of an asymmetrical mixing configuration, in the mixing channel, appears to greatly improve the quality of mixing, several studies have successfully reported the use of asymmetrical inlet flow conditions to further promote these asymmetrical mixing configurations, by using different axial [9, 6] and transversal [6] velocities, time-pulsing [12, 13] or by changing the geometry of the inlets [10, 11].

Regarding the use of asymmetrical geometries, Ansari et al [10] proposes a new geometry for the T-micromixer where the inlet channels are not vertically aligned, keeping, however, the tangential alignment. Designated as vortex T-mixer, the geometric asymmetry before the confluence region generates a vortex flow in the mixing channel, whose strength was found to increase with the Reynolds number. Thus, the interfacial area between the two liquids is extended, resulting in increased mixing efficiency, even at low Reynolds numbers, for which, in a simple T-mixer, the flow would occur in the stratified regime. The existence of asymmetry between the inlets of the mixer allowed for a substantial improvement of the mixing quality, in about 40% for a Reynolds number of 10 to 350% when the Reynolds number is 70, compared to its symmetrical counterpart. However, this mixer requires the manufacture of two layers of equal height, which are subsequently glued together to produce the vertical asymmetry between the inlet channels, with the precise alignment of the layers an added difficulty to the series manufacture process.

In a different study, by Calado et al. [11], the use of unbalanced inlets is approached in the form of a T-mixer with vertically aligned inlet channels, but having different widths. As opposed to the case shown above, an inherent advantage of this geometry is the possibility for direct manufacturing, without the need to subsequently proceed with the integration of additional parts. For this geometry, 5 different flow regimes were identified, in the range of Reynolds numbers between 50 and 310, as opposed to the three schemes identified above for the symmetrical T-micromixer. It was reported that an increase in the level of geometric asymmetry, between the mixer inlets, enhances the mixing quality and promotes the decrease of the Reynolds number for which transition between the regimes occurs, allowing for efficient mixing, even at the low typical Reynolds number of most microfluidic applications.

The performance of T-micromixers has been reported as also being greatly improved by time pulsing of the incoming flow rates of the two fluids to be mixed [12, 13]. At the confluence region, this results in the splintering of the interface between the fluids, therefore eliminating the parallelism between the two inlet flows. As such, the contact area between the liquid increases and the diffusion length is reduced, allowing mixing between the two to occur quickly and in a small volume. This method also has the advantage of not requiring additional parts in order to incorporate the temporal dependence on the incoming flow, being suitable for simple geometries, such as the T-mixer, and easily used in synergy with other methods, such as the introduction of obstacles to the flow, in order to further increase its revenues [12, 13]. Moreover, the shape of the signal, typically sinusoidal or square, does not appear to influence the degree of the mixing system [12].

In order to evaluate the degree of mixing in an objective manner, a unique parameter, \( \alpha_{mix} \), defined by Eq.1, has been commonly used [10, 11, 8]. This parameter takes into account the magnitude of changes that affect the distribution of sample concentrations during the mixing process, being based on the flow segregation index proposed by Danckwerts.

\[
\alpha_{mix} = 1 - \sqrt{I_s} = \frac{\sigma_c}{\sigma_{c,max}}
\]  

In Eq.1, \( I_s \) refers to the intensity of segregation, \( \sigma_c \) to the standard deviation and \( \sigma_{c,max} \) to the maximum standard deviation of the concentration field. This index varies between 0 and 1, with \( \alpha_{mix} = 0 \) corresponding to a fully segregated system, namely, stratified into two streams without interaction, and \( \alpha_{mix} = 1 \) to a homogeneous mixture. However, the concentration fields experimentally acquired are not continuous functions. Antithetically, they are rather discrete functions assuming a specific value of the grey scale intensity of each pixel in a specific cross section.

Introducing the variable \( \phi \), which represents the
normalized concentration profile of the two fluids in a cross section of the microchannel, and assumes the value 1 or 0 when the flow of only one of the fluids occurs, translating into a perfect mixture at a value of 0.5, the value of $\alpha_{mix}$, given by Eq.1, can be rewritten in a discrete algebraic formulation, as stated below in the Eq.2 [11], where $\phi_i$ represents the normalized concentration profile in a particular division of the analysed section and $N$ represents the total number of divisions. Eq.2 is used hereafter, throughout this work, to calculate $\alpha_{mix}$.

$$\alpha_{mix} = 1 - \sqrt{\frac{\sum_{i=1}^{N} (\phi_i - 0.5)^2}{0.5\sqrt{N}}}$$

(2)

The present work intends to study and characterize the performance of T-micromixers with variable inlet widths, where $W_{ia} \neq W_{ib}$, as shown in Fig.1 (a), when a pulsed signal is imposed to the incoming flow rates of the two fluids to be mixed, as well as the influence of the degree of asymmetry and the different signal pulse parameters, that govern the flow, in the mixing quality, comparing them later with either the symmetric case or with the use of a non-pulsed flow basis.

2. Materials, experimental methods and setup

In this section, a brief explanation of the manufacture process of the T-shaped micromixers used in this work is summarized, along with the description of the experimental setup.

2.1. Manufacture of T-shaped micromixers

The chips containing different micromixers, like shown in Fig.1 (b), were manufactured using polydimethylsiloxane (PDMS), acquired to Advanced ProSer SL, Spain, by soft lithography, in a clean and particle free environment, according to class 4 of Standard ISO 14644.1, ensured by the use of a vertical laminar flow cabinet, model ESCO AVC-4D1, to prevent the contamination of the channels.

The production procedure, briefly, consists of imprinting, in a 100 $\mu$m thick SU-8 50 resin layer (acquired to MicroChem, Germany), through the selective exposure, athwart an opaque photomask (acquired to JD Photo-Tools, United Kingdom), to ultraviolet radiation (by use of an UV exposition chamber, model UV-KUB, from Klo, France), of the microchannels geometry and removing the resin not exposed by immersion in PGMEA, creating the mould. The microchannels are then produced, through casting, by coating the mould with liquid PDMS and allowing the cure process to occur. Finally, the open chips are sealed with a glass lamella by adhesion (by means of a high high frequency generator, model BD-20, acquired to Electro-Technic Products, USA).

The dimensions of the produced microchannels were assessed by using FEG-SEM (field emission guns-scanning electron microscope - model JSM 7001F, from JOEL) images, examples of which are illustrated in Fig.1 (c) and (d), and are summarized in Table 1, with a maximum error of 3.22%. From the analysis of those figures it is possible to verify the quality of the manufactured microfluidic devices, the perpendicularity of the walls and the proper definition of the dihedral edges. The surfaces have, however, some roughness and the edges of the dihedral, although adequate to the present study, a slight curvature.

2.2. Experimental setup and methods

The experimental setup used in this work, as schematically represented in Fig. 2, consists of: two syringe pumps (models Nexus N5000 and N6000 from Chemix, USA); a highspeed and high-resolution monochromatic CMOS (complementary metaloxidesemiconductor) camera (model CR6000x2 from Optronis, Germany) to acquire the flow images, which is connected to an inverted microscope (model CX41 from Olympus, Japan), with a magnifying lens of $\times$10 and a tungsten halogen lamp of 50 Hz; and a PC to record the acquired images.

Throughout this work, deionized water and an aqueous solution of bromothymol were used as
Table 1: Geometrical characteristics of the manufactured microchannels.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( W_a ) (( \mu \text{m} ))</th>
<th>( W_b ) (( \mu \text{m} ))</th>
<th>( W_o ) (( \mu \text{m} ))</th>
<th>( L_o ) (cm)</th>
<th>( H ) (( \mu \text{m} ))</th>
<th>( D_H ) (( \mu \text{m} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>104.875</td>
<td>154.687</td>
<td>203.437</td>
<td>1</td>
<td>99.375</td>
<td>133.5</td>
</tr>
<tr>
<td>B3</td>
<td>100.312</td>
<td>100.312</td>
<td>200.625</td>
<td>1</td>
<td>100.937</td>
<td>134.3</td>
</tr>
<tr>
<td>B4</td>
<td>106.812</td>
<td>200.625</td>
<td>200.625</td>
<td>1</td>
<td>100.937</td>
<td>134.3</td>
</tr>
<tr>
<td>B5</td>
<td>102.188</td>
<td>175.312</td>
<td>200.625</td>
<td>1</td>
<td>99.375</td>
<td>132.9</td>
</tr>
<tr>
<td>P1</td>
<td>102.188</td>
<td>200.625</td>
<td>101.250</td>
<td>1</td>
<td>134.375</td>
<td>115.5</td>
</tr>
<tr>
<td>P2</td>
<td>105.938</td>
<td>203.437</td>
<td>300.000</td>
<td>1</td>
<td>97.969</td>
<td>147.7</td>
</tr>
<tr>
<td>P4</td>
<td>101.312</td>
<td>200.625</td>
<td>201.562</td>
<td>2</td>
<td>99.375</td>
<td>133.1</td>
</tr>
</tbody>
</table>

working fluids. This is so that both fluids can be differentiated in the recorded images, as the bromothymol dye, when dissolved in a basic solution as the one used, yields a dark blue colour solution \[6\]. In order to ensure that the working fluids exhibit similar properties, and thereby doesn’t interfere with the mixing process, the verification of their densities and dynamic viscosities was performed. By measuring the weight and volume of both working fluids, their densities were calculated, being the differences negligible. As for their kinematic viscosity, a viscometer (LVDV-II+ Pro, from Brookfield Engineering, USA) was used, yielding a difference of 2.38\%. Furthermore, a calibration of the syringe pumps was performed, attaining a maximum error of 5.73\%, ensuring that the debited flow rates were the same.

\[ \text{Figure 2: Schematic representation of the experimental setup: 1) and 2) Syringe-pumps; 3) T-shaped micromixer; 4) Waste deposit; 5) Light source; 6) CMOS camera; 7) Microscope; 8) PC. Adapted from [11]} \]

3. Digital image processing

Completed the experimental trials and, with the aid of the CMOS camera and the acquisition software, obtained the images of the flows within the manufactured T-micromixers, the methodological approach followed, using the Image Processing toolbox, in Matlab environment, for the digital processing of the captured images, showing the relevant components and eliminating elements of zero interest, is now presented. The CMOS camera available in the laboratory is monochromatic, which means each pixel in the acquired images is associated with an integer value in the grey scale, which ranges from 0 for the colour black and 255 for white.

The treatment of each individual image is divided into two separate sections. The first stage relates to the inspection and processing of the images as a whole, adjusting the contrast, brightness and gamma parameters, along with the filtering of undesired noise and cropping of the original image in the interest region, allowing for the clear visualization and discrimination of both inlet flows. As for the second stage, an analysis of the flow inside the mixing channel, evaluating the mixing quality, is performed. The intensity profile, in the analysed cross section of the mixing channel, which is located 740 pixels, equivalent to 1057 mm, from the vertical wall common to both inlets, is determined and normalized according to the mean intensities of the inlet flows, yielding \( \phi \), which is then used to gauge \( \alpha_{mix} \), according to Eq.2.

4. Results and Discussion

In this section, the results regarding the study of T-micromixers, with variable inlet widths, as shown in Fig.1 (a), are presented. Firstly, a study of the mixing quality along increased \( Re \) is presented, for the different T-mixers. Then, imposing a pulsed signal on one or both incoming flow rates of the two fluids to be mixed, several pulsed flow configuration are studied, to gauge the effect of the different parameters that govern the signal. To finish, a study on the effect of varying the width and length of the mixing channel is presented.

4.1. Effects of the asymmetry between the inlets

In the current section, an evaluation of the performance of T-micromixers, where the degree of geometric asymmetry between the inlets is changed, more specifically, the width of the cross section of
the right inlet channel, $W_{in}$, keeping the geometry of the opposing channel unchanged, is carried out. The performance analysis of the different micromixers is enacted according to the Reynolds number in the mixing channel.

Figure 3: Effect of the asymmetry between the inlet channels: $\alpha_{mix}$ as a function of $Re$, for the microchannels B3 (non filled red circles), B1 (filled blue circles), B5 (filled grey triangles) and B4 (filled yellow squares). Above the graph are the identified regimes for the different mixers.

From the analysis of the results of this study, shown in figure 3, it is clear that the performance of T-micromixers benefits from an increase in the Reynolds number, denoted by a boost in the mixing quality. This trend follows that which is presented in other studies exclusively for symmetrical [14, 15, 16] and asymmetrical T-micromixers [11].

Regarding the asymmetric T-mixers (B1, B5 and B4), their behaviour, depending on the Reynolds number, is divided, in the literature [11], into five distinct regimes, numbered from I to V. Similarly, the present study also verifies the same partition, based on the characteristics of the flow and the concentration profiles, as exposed in Fig. 4 for the different regimes identified. Favouring an increment in the outflow Reynolds number an increase in the mixing quality, it can be seen that regime V is the most suitable as the operating range of asymmetrical T-mixers. This can be explained by the different flow configurations in the various regimes mentioned above. The rupture of the interface between both fluids, observed in the first place, for regime II, promotes the spreading of bromothymol solution into the region previously occupied by water and influences the mass transport by advection, between the two fluids. In regime V, with the total rupture of the interface and the formation of vortex structures, strong mass transport by advection in the transverse direction occurs, thus improving the mixing quality, as seen in Fig. 4 (e) and (f).

Analogously to the asymmetric instance, the results for the symmetrical case, shown in Fig. 3, also follow what is patented in the literature. As evidenced in section 1, the onset of the engulfment regime results in the generation of secondary flows in the direction transverse to the main flow, which produces the deformation and entanglement of streamlines, ensuring an added impact in the mixing quality, when compared to the symmetrical regimes that occur at lower Reynolds numbers, as can be seen from the comparison between Fig. 5 (a) and (b), for the symmetrical vortex regime and 5 (c) and (d), for the asymmetrical engulfment regime.

Comparing the results obtained for the symmetrical and asymmetric instances, in Fig. 3, it follows that the use of asymmetrical T-micromixers presents itself as most beneficial to the quality of mixing, resulting a higher degree of asymmetry in greater benefits. Also, the increase of the level of geometrical asymmetry promotes promotes the premature transition, for Reynolds numbers between 50 and 120, to regimes with asymmetrical flow configurations, thus ensuing a higher mixing quality. In contrast, this transition only occurs for the symmetrical case for a Reynolds number of about 150, with the beginning of the engulfment regime.

4.2. Pulsed Flow

The now presented study deals with the imposition of a pulsed signal to the flow of one or both mixer inlets, to assess if the resulting perturbation translates itself in an increased mixing quality. Within the given magnitude, a square signal is applied, as the sketched in Fig. 6, and varying the parameters that define it. A positive pulse is defined herein as the one where the flow rate exceeds the average flow, contrary to the negative pulse.

This section begins with the investigation of the effects of the application of the pulsed signal exclusively to each of the entries of the T-micromixers. Since in each test, only one of the inlet flow is pulsed, points 1, 2 and 3 refer to this pulse, in Fig. 6. Afterwards, the separate influence of each parameter, which defines the pulse signal, is gauged, including its amplitude, frequency, and since, in this section, the signal is applied to both inlets, the phase difference between the signals. It is of note that, in this second section, points 1, 2 and 3 always refer to the pulse signal applied to the inlet where the flow of bromothymol solution happens, except when indicated otherwise, for individual cases.

4.2.1 Imposing the pulsed signal to one of the inlets

In the study presented then seeks to determine how the imposition of a pulsed signal to one of the
inlet flow affects the mixing quality. In a more specific way, it aims to also check the function of the pulse behavior depending on inlet channel geometry to which it is applied. In this sense, the asymmetric channel B1, corresponding to the intermediate asymmetry channel, and B4, the most asymmetrical, as well as the symmetrical channel B3, are used. For each analysed T-mixers, a pulsed signal was separately imposed exclusively to each of the inlets, with the exception of symmetrical channel where, due to this unique feature, only one of the inlets was investigated. In each test, a continuous flow of flow rate equal to the average of the pulse was applied to the opposite inlet.

First, from the analysis of Fig. 7 and 8, it easily follows that the mixing quality is higher when the flow rate at narrower entrance is greater. Thus, when the pulse signal is applied to this inlet, the maximum performance of the T-mixer occurs at the end of the positive pulse, indicated in Fig. 6 as

Figure 4: Illustrative examples of the flow configurations and concentration profiles for the different regimes identified in the asymmetrical T-mixer B5.
Figure 5: Illustrative examples of the flow configurations and concentration profiles for the transition between the vortex and the engulfment regimes, for a Reynolds number near 150, in the symmetrical T-mixer B3.

Figure 6: Example of the square pulse signal applied to the inlet flows. 1,2,3: temporal instants for evaluating the mixture degree. The orange dash line represents the mean between the maximum and minimum amplitude of the pulse. Adapted from [11].

point 2. At the opposite context, when the signal is applied at the widest entrance, this happens at the beginning of the positive pulse, expressed in Fig. 6 as point 1, conjecture supported by the images of the acquired flow and the concentration profile, in the studied section, illustrated, for the more asymmetric channel B4, in Fig. 9 (a) and (b). In both cases, the point at issue is correspondent to the instant when the flow rate at the narrower inlet ceases to be higher.

Figure 7: Application of a pulsed signal to the largest inlet of the channel B4.

Regarding the effect of varying the degree of asymmetry, it can be seen that an increase of this parameter translates into superior mixing qualities at the point where the flow rate in the narrowest inlet is higher, while in the opposite situation, a slight reduction in $\alpha_{mix}$ can be verified. Due to the geometrical configuration of these T-micromixers, with an inlet wider than the other, the flow that occurs at the widest inlet is faced with lower resistance from
the opposite flow, compared to the symmetric case, when circumventing the dihedral, trend that results in a curtailed movement of the fluid elements in the transverse direction of the mixing channel. Therefore, when the flow at the widest inlet has a higher flow rate than the opposite inlet, its momentum is transferred to the mixing channel, instead of being totally used in the disruption of the interface between the two fluids, as illustrated in Fig. 9 (c) and (d). This results in less interference with the contrasting fluid and, with the increase in asymmetry, the lower the mixing quality. When the flow in the narrower inlet has a higher flow rate, this phenomena is reversed, reducing the amount of motion transferred from the flow of the wider inlet to the mixing channel, and promoting the movement of fluid elements in the transverse direction and the disruption of the interface between the fluids, resulting this conjunction of circumstances in an improvement of the mixing quality, as verified from Fig. 9 (a) and (b), proportional to the degree of asymmetry that causes this occurrence.

### 4.2.2 Effect of the parameters that characterize the pulsed signal

In this section, the different parameters that define the pulsed flow signal are considered. With the imposition of pulsed signals to both input flows, the degree of mismatch between the square waves that make up the signals, concept here designated as phase difference, can be altered. Regarding this parameter, five separate cases are contemplated, by gradually offsetting the signals 45°, from the position in which they are in phase, corresponding to 0°, to the one in which the phases are opposed, which corresponds to a gap of 180° between the applied signals.

Through the analysis of Fig. 10, which present the results of this study, it is clear that the use of inlet flows with phase opposition present a greater benefit, when faced with those made in phase, since the mixing quality is always superior. In addition, the mixing quality increases in a gradual manner as the phase shift between the signals applied to the inlet flows becomes greater, hitting its highest point for phase opposition, as already stated.

As for the influence of the amplitude of the imposed signals, the signals detailed in Tab. 2 were applied to both inlet flows. The results of test 1, for the microchannels B3, symmetrical, and B4, the most asymmetrical, are displayed in Fig. 11.

From the analysis of the Fig. 11, it is clear that, for any of the tests given in Tab. 2, the main parameter that influences the mixing quality in the outlet channel is the average flow rate, around which the maximum and minimum amplitudes of the signal oscillate, with the maximum mixing quality verified for the largest average flow rate studied. This conclusion is similar to that seen for continuous flow in this type of micromixer, study presented in section 4.1.

For the symmetrical T-micromixer, B3, the same growing trend of mixing quality with the average flow is seen, but it appears that the quality at point 2 is similar to that found in point 1, feature of this microchannel that may be explained by the symmetrical nature that the geometry ensures to the flow, when comparing points 1 and 2.

### Table 2: Tests performed for studying the influence of the amplitude of the pulsed signal in the mixing quality.

<table>
<thead>
<tr>
<th>Test</th>
<th>Phase (°)</th>
<th>Flow rate (mean) (µL/min)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>200 - 1200 (700)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 - 1500 (1000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 - 1800 (1300)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>800 - 1200 (1000)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 - 1500 (1150)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>800 - 1800 (1300)</td>
<td></td>
</tr>
</tbody>
</table>

For the frequency analysis, pulsed signals in phase opposition, with maximum and minimum flow rates 1800 and 800 µL/min, respectively, are applied to both inlet flows. The frequency is varied between 1 and 5 Hz. The results of this study are presented, for channel B4, in Fig. 12.

Regarding the effect of altering the frequency, it is inferred that the mixing quality in 1 decreases with increasing frequency, as opposed to what is documented for point 2, where, for asymmetric micromixers, a surge is observed. The behaviour regarding point 1 occurs since, until the instant immediately before the change of flow rate, there isn’t enough time for the flow to develop the configura-
Figure 9: Illustrative examples and concentration profiles, at points 1 and 2, of the application of a pulsed signal in phase opposition, with maximum and minimum flow rates of 1800 and 800 µL/min and frequency 1 Hz, to the wider inlet of the T-micromixer B4.

Figure 10: Results of a pulsed signal application, varying the phase difference in the inlet of the micromixer B4. The mixing quality for a phase of 0° is identified by the green cross, for the phase difference of 45° by a blue horizontal line, for a phase difference of 90° by an orange diamond, for a phase difference of 135° by a gray triangle and, for a phase difference of 180° by a yellow square. The mean flow rate of 1000 µl/min is identified by unfilled blue circles.

Figure 11: Results of a pulsed signal application, varying the amplitude in the inlet of the micromixer B4. The mixing quality at the first point is identified by a blue square. On the other hand, the mixing quality at the second point is represented by an orange triangle and at the third point by a yellow circle. The mean flow rate of 1300 µl/min is identified by unfilled green circles.

at point 2, the increased pulsating characteristic of the flow, with more flow variations for the same sampling time interval, does not allow the flow to completely lose the merged structure achieved at
point 1. As for the symmetric mixer, the same decreasing trend is seen for point 1, however, the mixing quality in point 2 is similar to that of point 1, for the same reasons stated above.

5. Conclusions

As suggested, the geometrical configuration of micromixers can be used to improve the mixing process in microfluidic systems. For continuous flows, the use of asymmetrical inlets has been demonstrated to achieve superior mixing qualities, assessed by the index $\alpha_{mix}$, when compared to its symmetric counterpart, with the maximum quality verified for the most asymmetrical mixer, B4. Also, it has been shown that regimes with asymmetrical flow configurations consist in the desired operation range for T-micromixers, both symmetrical and asymmetrical, and that the asymmetrical geometries promote the premature transition to regime where these conditions are verified, increasing the mixing quality.

Regarding the use of pulsed flows, these have been shown to greatly benefit the performance of T-mixers, either symmetric and asymmetric. As presented, the use of signals, applied to both mixer inlets, in phase opposition, with a high mean flow rate, for lower frequencies, appears to be the most favourable arrangement of the signal parameters to achieve high mixing qualities in the outlet.

In short, the use of T-micromixers with variable symmetry between the inlets, when used in synergy with pulsed flow, appears to be a simple and handy way to encourage the mixing process, for which satisfactory levels of quality are thus easily achievable.

References


