Experimental mixing characterization of Newtonian fluids mixing in asymmetric T-micromixers

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Abstract
Mixing in microfluidics represents a challenge to the scientific community due to the difficulty in promoting turbulent flows, which have high mixture capacity. Therefore, three T-shaped micromixers, with asymmetric inlets of 19, 36 and 70% were manufactured in order to evaluate their mixing capacity. The manufacturing procedures were based on soft lithography using two fundamental materials: the photoresist resin to build the mold and an optically transparent polymer, which constitutes the microchannels chips. From the tests made to the three manufactured channels, with Re values in the outlet ranging between 50 and 310, five different regimes were identified. After that, the flow was evaluated in terms of mixture efficiency through the channel by two different parameters: the first one represents the segregation index of the flow and the second quantifies the diffuse mixture potential after passing through the T-junction. The study concluded that the increase on the channels geometrical asymmetry promotes the decrease on the regime transition values of Re and improves simultaneously the mixture quality produced at the outlet.

Keywords: microfluidics, mixing, microfabrication, asymmetric T-micromixers

1. Introduction

Microfluidic mixing is being widely studied as an approach for biological and biomedical devices, aiming to achieve a way to fast molecules detection, disease's diagnose or drug delivery with the main benefit of spending the less resources, reagents or drugs, as possible. Lab-On-Chip (LOC) and, in general, micro total analysis systems (µ-TAS) are micro-mixers based devices that represent the most interesting late development in micro-engineering investigation, about this subject [1,2].

In any case, mixing quality is a determinant factor in whether or not this devices are reliable. In contrast to macro dimensions, micro structures with dimensions such as $10^{-4}$ to $10^{-6}$ meters, represent a challenge as the surface-to-volume ratio is much higher than in macro-scale, and so being surface events dominant when compared to volume ones [3]. As a consequence of this, turbulence is extremely difficult to achieve in microfluidics, making a fast and good mixing hard to achieve. Also, the pressure drop, in dimensions of this order, makes micro-engineering essentially different from known macro-scale problems.

Concerning the way of promoting mixing, micro-mixers can be classified as active, if there is an external energy source which produces agitation or perturbation of the laminar flow, or passive, if mixing is promoted only through channel geometry, projected to create advection mechanisms besides molecular diffusion. Present work is focused on passive mixers, as they have already proved to produce good mixing times with less fabrication costs, when compared to active ones, therefore representing a better cost-benefit ratio [2].

Besides its simple configuration, T-shaped passive micro-mixers already showed great results in mixing quality experiments. With this specific geometry, two symmetric and opposing inlet streams enters together throughout one perpendicular outlet channel, referred as mixing channel. The major advantage of this configuration lies on the breaking up of the outlet's axial symmetry which happens from a particular Re value, allowing fair advection mixture.
Moreover, there were identified on T-mixers three different laminar flow regimes, depending on Re. For low Re, flow is stratified, having no mixture induced as both streams are able to follow the outlet channel walls without any disruption on the interface. At this point, mixing is only achieved through diffusion events, which are very slow. At medium Re, vortex flows will be possible to observe. Despite having a quite similar aspect when compared to stratified ones, in this case both flow streamlines turn into well defined, regular and symmetric vortices, providing some drag between fluids and therefore improving mixture quality. Nevertheless, in this laminar regime mixture quality is still poor, as diffusion events continue to dominate. Finally, for higher Re, the flow loses their symmetric configuration, as axial border between flows dies out. In this regime, called as engulfment regime, inlet flow streamlines no longer follow channel walls, strongly improving mixture quality by mass advection [4–7].

However, regimes are not only dependent on Re range [4–7], but they also seem to strongly depend on the micro-channels geometrical properties, such as the relation between the width and the height. So, in order to well characterize the flow regimes in T-mixers with a single parameter, a dimensionless number K, named as identification number [4], was proposed, mainly with the goal of finding a way to calculate the critical Re above which engulfment regime will be achieved, for any T-mixer. The following relation has been experimentally and numerically validated [6, 8–10].

\[ K = Re^{0.82} AR_{i}^{-0.8} \left( \frac{D_{hi}}{D_{ho}} \right)^{-1.5} AR_{o}^{0.15} \] (1)

In the previous equation, AR is the ratio between the width and the height of the channel in case and \( D_{h} \) the hydraulic diameter.

In addition, a valid mixture quality measurement is mandatory to quantify the mixing obtained at the outlet. The \( \alpha_{mix} \) parameter used here, based on Danckwerts segregation intensity parameter (I5) [7] allows a quantitative conversion from fluid concentration (depicted through grey scale image intensity) to a mixture degree, hence allowing the evaluation of mixture for different flow regimes, at different channel locations. As said above, results have shown that engulfment flows lead to stronger quality of mixture.

\[ \alpha_{mix} = 1 - \sqrt{I_5} = 1 - \frac{\sigma_{c}}{\sigma_{c,max}} \] (2)

In the previous equation, \( \sigma_{c} \) is the the standard deviation of the concentration field and \( \sigma_{c,max} \) the maximum standard deviation.

Finally, some studies involving the use of asymmetric inlet conditions to improve quality of mixing, such as different axial velocities, transversal velocity components or even different viscosities, have been demonstrated to work [8, 11, 12]. However it wasn’t found any study on asymmetric inlet geometries, which are the remaining parameter on the definition of Re to evaluate. With this in mind, the goal of the present work is to study this geometries, evaluating the influence of the asymmetry on the flow behaviour for Re ranging from 50 to 310, as well as quantify the mixing quality achieved by them.

2. Experimental Setup

Besides the main purpose of the present work lies on the qualitative and quantitative analysis of mixing, channel manufacturing was performed and, therefore, must be given special importance. So, the experimental apparatus concerns not only on what is needed for the flow visualization, but also in the manufacturing processes to produce the three chips used in this study.

2.1. Microchannels manufacture

It was decided to include this chapter once the experimental manufacturing procedures of softlithography are quite simple and the costs are low. However, the main advantage is the possibility of reproducing a pre-used
damaged channel. All the following processes, illustrated in figure 1 were made within an extremely clean and micro-dust-free environment, to guarantee no impurities inside the final channels.

The first step is to engrave the channel profile in a thick polymeric resin layer, through selective exposition of UV radiation, which is a process called as photolithography. The following step consists in removing off the material that were not exposed to radiation by the use of a developing agent, and so, getting the mold of the channel. Finally, the projected channel is made through casting by pouring a pre-polymer, in liquid phase, into the mold. As it solidifies, after mixing with a reticulation agent, the final chip with the channel geometry intended inside is achieved. The used polymer is PDMS (Polydimethylsiloxane), as its properties are well established to be compatible with the production of micro-structured devices. Finally, PDMS counter-mold is removed and the channel must be sealed with a glass lamella.

![Diagram of photolithography process](image)

From this manufacturing process, three PDMS chips of different microchannels channels were made, like the one presented in figure 1. As this study is focused on asymmetric conditions, all channels are made in such a way that the two inlets differ only in width. The geometries achieved are summarized in table 1.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$W_a$</th>
<th>$W_b$</th>
<th>$W_w$</th>
<th>$H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>163</td>
<td>194</td>
<td>278</td>
<td>71</td>
</tr>
<tr>
<td>B</td>
<td>169</td>
<td>230</td>
<td>282</td>
<td>69</td>
</tr>
<tr>
<td>C</td>
<td>142</td>
<td>242</td>
<td>238</td>
<td>98</td>
</tr>
</tbody>
</table>

2.2. Experimental apparatus

After testing and evaluating the microchannels reliability, several flow trials were performed with deionized water, in order to characterize T-junction the internal mixing of the two inlet flow with similar thermo-fluidic properties. To
distinguish both transparent flows in order to characterize the flow regimes, a dye had to be added to one of the fluids. For that it was selected bromothymol blue powder as appropriate dye to dissolve in water, since it doesn’t changes the viscosity and density of the water and presents, in this experiment’s conditions, a dark blue color, easily detected by the monochromatic camera available, and thus enabling an good identification of each inlet fluid inside the microchannel.

The experimental apparatus used in these trials consists in a pumping system, consisting on two syringe-pumps and an optical and image acquisition system, allowing the continuous image capture and record of flow, by one high speed CMOS and monochromatic camera, connected to a microscope. Also, a methodology for image computational treatment is necessary for correct interpretation of the results. In figure 2.2 there is a schematic representation of the experimental installation.

2.3. Digital Imaging Processing

During experimental image capture, microchannel interior flow is visualized through digital images, captured by CMOS camera, attached to the microscope. However, flow recording may catch other undesirable aspects related to microscopy handicaps, such as blurs, shades or dots, corresponding to elements present in other planes
different from the focused one, in the lens or inside the microscope structure. As a consequence, applying a
digital image treatment is fundamental for assessing flow regimes features, reducing captured noise to irrelevant
levels. In this work's approach, MATLAB was the chosen environment for this treatment, often through its Image Processing toolbox.

The CMOS camera used is monochromatic, and as a result, images are obtained in a grey-scale. Corresponding
computational entity is a matrix of dimension equal to the image's resolution, in which each entry is given by the
value of the pixel intensity. Intensities vary from 0 to 255, where 0 corresponds to the absence of intensity, thus
codifying black and 255 to white.

Digital imaging processing is made by two stages. First, in a whole image approach, operations are applied
to improve contrast and therefore have a more distinct flow description. Also, dilution of some visual noise is
accomplished. Second, concerning only the interior channel region, a set of operations are applied in order to
maximum reducing of noise. This last treatment wasn’t applied directly on the record images, but on the profile of
light intensity calculated for the mixing channel section to be analysed, when evaluating the mixing quality.

As said, the quality mixing is going to be evaluated from the intensity profile taken for the considered section on the
mixing channel. For that, it had to be calculated the average pixel intensity for water region and for bromothymol
region, when completely segregated (unmixed) and then applied some manual filters to make the profile represent
properly the real flow configurations. The averages calculated for the unmixed bromothymol and water were used
to adimensionalyse the intensity of the pixels.

3. Results and discussion

The results about to be shown were obtained for three microchannels with the main geometric features described
on the table 2. As it can be seen, the microchannel A reveals the less asymmetric inlets, while microchannel C
reveals the most.

<table>
<thead>
<tr>
<th>Microchannel</th>
<th>ARa/ARIa</th>
<th>ARo/ARIa</th>
<th>ARo/ARIb</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.19</td>
<td>1.71</td>
<td>1.43</td>
</tr>
<tr>
<td>B</td>
<td>1.36</td>
<td>1.67</td>
<td>1.23</td>
</tr>
<tr>
<td>C</td>
<td>1.70</td>
<td>1.68</td>
<td>0.98</td>
</tr>
</tbody>
</table>

3.1. Flow regimes

For the description of the identified flow regimes, equally observed for all three microchannels, the images taken
for microchannel A are used, as well as the respective intensity profiles. Also, the flow injected in the wider
entrance was the bromothymol one.

For the lowest values of Re, between 57 and 76 the flow is completely segregated, as seen in figure 4(a), with a
clearly defined interface dividing both the inlet streams, in which the only mixing mechanism active is diffusion.

Raising the inlet flow rate, the flow enters in the regime II, remaining like that for Re = 95 to 133. Here, some of
the bromothymol flow crosses the interface, mixing with water through advection. However, this behaviour was
only detected for the inlet from the wider entrance.

At a given point, this effect that has contributed positively to the mixing quality invert, since the bromothymol
layer start to accumulate only near the opposite wall, and, therefore, the water recovers some of his original
concentration. This was defined as the regime III and visualized for Re = 143 to 172.

Suddenly, at Re = 190, the interface well distinguished hitherto vanishes, creating a new region of flow well mixed,
as can be seen in figure 4(b).This regime IV was visualized for Re = 190 to 248.

Finally, for Re = 267 to 305 it was identified the regime V, similar to the regime described as engulfment, in the
literature presented [5,7,11]. In this, the flow configuration breaks in the T-junction into a alternate multilayer flow
of water and bromothymol, with some mixture already provided by advection and well suited for fast mixing by diffusion in the upstream of the mixing channel, since the diffusion lengths are quite small. This description is shown in figure 4(c).

3.2. Mixing quality

For the measurement of the mixing quality achieved in the outlet channel, it were defined two parameters based in different concepts.

The first one was already presented in equation 2, based on the segregation level of the flow.

The other one is based on the amount of concentration changes along the profile acquired for each trial and shows the diffusive potential of mixing of the flow in the upstream, since diffusion is proportional to the concentration gradient. This parameter, $\gamma_{mix}$, is defined in the following equation, where $N$ is the number of pixels in the section used, and $\phi$ the corresponding pixel intensity adimensionalised:

$$\gamma_{mix} = \frac{\sum_{i=1}^{N-1} |\phi_{i+1} - \phi_i|}{N - 1}$$

This parameter reveals to be quite useful to a better understanding of the mixing obtainable with each of the regime, when the $\alpha_{mix}$ can’t, since, for example, the regime V concentration profile (Figure 4(c)) seems to be well divided but also quite segregated. For this case, $\gamma_{mix}$ complements the mixing information given by the previous variable.

With this in mind, in figure 5 its shown the mixing quality results, by both the parameters defined, obtained for all three microchannels in all Re numbers tested.

As it can be previously predicted, the mixing quality improves with the Re, for all asymmetric geometries, being the regime V the one able to produce the better mixing, both by advection until the section studied and diffusion after that.

Also it’s possible to observe that, as higher is the asymmetry of the inlets, lower is the Re value of each regime identified. This fact reinforces what it was stated before, about the better mixing efficiency of the most asymmetric microchannel.

To a better understanding of the reasons to the variations of the mixture achieved with those three microchannels, it is presented in figure 6 the images from the regime V flow in each of them. In here, it’s clearly seen that the most asymmetric geometry (microchannel C) produces a better divided flow, therefore being much better for mixing, since the flow is laminar in the upstream, which means that the only active mixing mechanism from there on is diffusion.
Figure 4: Most relevant flow regimes illustration and the corresponding concentration profile, acquired from the marked section.
Figure 5: Mixing quality verified in three microchannels. The red circles refers to the less asymmetric (microchannel A), the green diamonds for the intermediate asymmetry (microchannel B) and the blue squares the most asymmetric (microchannel C). The bars above identify the range of each working regime for each channel.

Figure 6: Regime V at $Re \approx 300$ in the three manufactured microchannels.
4. Conclusions and future work

T-shaped micromixers have been previously investigated about the inside flow regimes and mixing quality achieved. However, there wasn’t been done any study on the impact of asymmetric inlets, even though there has been proven that asymmetric inlets viscosities and velocities improve mixing quality at the outlet. With this in mind, the presented work fills this gap on T-mixers performance analyses.

There has been shown, for three asymmetric T-mixers, with $AR_{i_b}/AR_{i_a}$ equal to 1.19, 1.36 and 1.70 and for $Re$ values ranging from 50 to 310, that five distinct regimes occur inside of them and that the asymmetry causes the anticipation of the beginning of each regime, so as higher the asymmetry of the channels inlets is, the early the regimes occur.

About the mixing performance, it was undoubtedly verified the growth of the mixing quality achieved in the outlet channel with $Re$ value, so being regime V the best one. The effect of the asymmetry, as been concluded to produce better results, since the flow reaches regime V for lower $Re$ and the flow configuration breaks up more intensely.

References