Investigation of high frequency external perturbation effects on flow in a T-shape microchannel by $\mu$LIF technique

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Abstract. Investigation of high frequency external perturbation effect on flow inside T-shape microchannel was examined. In-phase pulsations of different frequencies were added to both inlets of the T-shaped microchannel to study mixing by means of Micro Laser Induced Fluorescence ($\mu$LIF) technique. For all flow regimes studied, mixing enhancement was obtained. Significant enhancement can be achieved at the beginning of the outlet channel operating in steady asymmetric regime (Re=186) by forcing at certain frequency ranges ($f = 500$Hz, $f = 800$Hz). Mixing suppression was also observed for two flow regimes (Re = 400, $f = 1000$Hz) and (Re = 120, $f = 700$Hz).

1. Introduction
Mixing in microchannels is important process for various biomedical and chemical applications. Microchannels usually operate in laminar or stratified flow conditions when mixing is governed by diffusion, which gives low mixing rate comparing to turbulent mixing. Therefore mixing enhancement in micromixers is an important topic. T-shaped micromixer has a simple and robust geometry. Flow regimes in T-shaped micromixer for different Reynolds numbers have been extensively studied previously. Engler et al. [1] showed that vertical flow arises in the microchannel because of Dean vortices. The critical Reynolds number, when Dean vortices lose their symmetry is 150. Mixing efficiency of two liquids within the range of Reynolds numbers from 50 to 1400 is investigated in [2]. Gobert et al. [3] numerically examined unsteady periodic regime. Mixing in a T-shaped microchannel for Reynolds numbers from 100 to 500 was done in [4]. The authors obtained the velocity and concentration fields using $\mu$PIV and $\mu$LIF techniques. The mixing efficiency was found to be highest for moderate Reynolds numbers (Re = 240-400) with S-shaped vortex flow and unsteady periodic flow regimes.

In order to study possibility to control and enhance mixing, a few authors investigated pulsed flow as inlet condition in T-shaped active micromixer. W B Mao and J L Xu [5] showed that mixing at low Reynolds numbers can be enhanced by pulsed flow with high amplitude. The higher the frequency the more enhancements can be achieved [6]. Ma et al. [7] found that there are optimal pulsation frequencies. Phase shifting of the pulsations will affect mixing as well [8]. All studies cited here used pulsed flow with high amplitude pulsing to get stratified flow in outlet channel. Contrary, in our paper we studied low amplitude perturbation, which can be enhanced by natural instability of the flow at
moderate Reynolds numbers, and lead to mixing enhancement with less energy consumption needed to force the flow.

2. Experimental setup and conditions
Experiments were carried out on the microchannel setup equipped with syringe KD Scientific pump with two outlets. Carl Zeiss Axio Observer.Z1 microscope with a number of lenses (figure 1) and filter set were used to get fluorescence images. To create the external disturbances of the flow with controlled frequencies, special excitation system based on the piezoelectric actuator was integrated in a hydrodynamic loop. Piezoelectric actuator with maximum motion 150 \( \mu m \) was preloaded by 1kN force and was driven by piezo drive with sine signal.

A T-shaped microchannel made of optically transparent material SU-8 with dimensions of 120×120×240 \( \mu m \) (height, width of the inlet channel and the width of the outlet channel) was mounted on the microscope stage. The variation of flow regime in microchannel is defined by Reynolds number, \( Re = \frac{U_0 D_h}{\nu} \) where \( U_0 \) is the mean flow rate velocity in outlet channel, \( D_h = 4 S_{mix} / P_{mix} = 160 \) \( \mu m \) is hydraulic diameter, \( S_{mix} \) and \( P_{mix} \) are an cross-section area and a perimeter of mixing channel, correspondingly, \( \nu \) is the kinematic viscosity of the flow. The experiments were carried out at Reynolds numbers \( Re = 120, 186, 300, \) and \( 400 \). All experiments were done with flow rates equal for both inlet channels. The high frequency external perturbation is generated in the same phase on both inlets of the microchannel with the frequency \( f \) up to 1000 Hz. The piezoelectric actuator motion conforms sinusoidal waveforms (\( U^n \)) from signal generator intensified by dynamic piezo driver. Amplitude is fixed to 100 \( \mu m \), which corresponds to \( 3.14 \cdot 10^{-5} m^3/s \) of squeezing volume for \( f = 1000 \) Hz. The schematic of the active mixing on microchannel are showed in figure 2. The working liquid was distilled water.

**Figure 1.** Sketch of the experimental setup

**Figure 2.** Schematic of the active mixing on T-microchannel
3. Measurement technique
To analyze flow patterns and a mixing efficiency in outlet channel Micro Laser Induced Fluorescence (µLIF) inverted in microscope was used. One inlet of microchannel was fed by the distilled water and the second inlet was fed by solution of distilled water with Rhodamine 6G dye. The concentration of the solution was 15mg/l. A mercury lamp was used for flow illumination. Band pass filter with a maximum transmission at 532 nm and beam splitter with 560 nm cutoff frequency were used to illuminate and register intensity of the fluorescent dye. Images from CCD camera (10 bits, matrix resolution 2048x2048 pixels) were processed in Actual Flow software to get intensity calibration and to calculate concentration fields.

4. Results
Figures 3-6 show time-averaged concentration fields for different Reynolds numbers and various perturbation frequencies together with the mixing efficiency calculated in outlet channel on distance equal to one and five hydraulic diameters $D_h$ far from the inlet. In the concentration fields, the red color corresponds to liquid with Rhodamine, the blue one - to distilled water. The green color corresponds to concentration range $c = 6.1\pm 8.9 \text{ mg/l}$ and shows the area of complete mixing. Frequency $f = 0 \text{ Hz}$ corresponds to undisturbed flow case (figures 3-6 a).

In conducted experiments, the mixing efficiency was calculated using a concentration profiles measured at distances equal to $D_h$ and $5D_h$ from inlet channel (figures 3-6). The estimate of mixing efficiency was made using Dankwerts segregation intensity $I_M$ [9]: $I_M = 1 - \sigma / \sigma_0$, where

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (c_i - \bar{c})^2, \quad \bar{c} - \text{is the average value of the concentration,} \quad \sigma_0^2 = \bar{c}(c_{\text{max}} - \bar{c}) - \text{is the maximal root-mean-square deviation for mixing of liquid with concentration 0 and } c_{\text{max}}.$$

Thus, the liquids are completely mixed at $I_M = 1$, while segregated at $I_M = 0$.

The first series of experiments are presented for the stationary vortex flow regime $Re = 120$ (figure 2). For this regime, increase of the external perturbation frequency to 700 Hz leads to thinning of interface between liquids (figure 3b). However, for $f = 1000 \text{ Hz}$ the interface width increases (figure 3c) from 10% of the channel width at the distance $1D_h$ to 26% at distance $3D_h$. One can see also the insignificant decrease of interface width further downstream. In figure 2d the mixing efficiency increases within a range of frequencies from 0 Hz to 500 Hz at a distance equal to $D_h$ from the entrance by 5%, and at a distance of $5D_h$ - by 9%. Here in after the change in mixing efficiency is expressed in % and presented in comparison with undisturbed case in the same cross-section. As the frequency increases further up to 675 Hz, the mixing efficiency decreases by 10.6% at a distance of $D_h$ and by 5% at a distance of $5D_h$ comparing to the undisturbed flow. Further increasing the frequency leads to growth of the mixing efficiency by 16% at a distance of $5D_h$, as well as by 9% and 6% at a distance of $D_h$ for frequencies 800 and 1000 Hz, respectively. According to the visualization of mixing patterns efficiency increases significantly.

![Figure 3. Concentration fields – a, b, c and mixing efficiency – d, Re = 120](image-url)
For stationary asymmetric vortex flow regime $Re = 186, f = 0 \text{ Hz} \ (\text{figure 4a})$ one can observe that the flow in outlet channel is structured. However, the plots of concentration fields sharply change in case of the external perturbations corresponding to 500 and 800 Hz (figure 4b,c).

![Figure 4. The concentration fields – a, b, c and the mixing efficiency – d, Re = 186](image)

Concentration fields become homogeneous. We can suppose that it happened due to Kelvin-Helmholtz instability in liquid layers of jets interacting at the entrance of the outlet channel. The mixing efficiency increases by 35 and 17% with frequency raise to 500 Hz at a distance of $D_h$ and $5D_h$, correspondingly (figure 4d). A further increase of the external perturbation frequency up to 650 Hz leads to a decrease in the mixing efficiency, however it is greater by 12% comparing to the case of undisturbed flow. The mixing efficiency increases by 24% for the frequency growth up to 800 Hz at a distance of $D_h$ and by 11% at $5D_h$. Within the frequency range from 800 to 900 Hz the mixing efficiency decreases to that for 700 Hz. Next, the mixing efficiency increases by 6% for frequencies up to 1000 Hz.

For the periodic unsteady flow regime $Re = 300 \ (\text{figure 5})$, the mixing efficiency changes insignificantly, namely up to 3%.

![Figure 5. The concentration fields – a, b and the mixing efficiency – c, Re = 300](image)

In figure 6, which corresponds to $Re = 400$, we can observe that for undisturbed case ($f = 0 \text{ Hz}$) the concentration field is homogeneous in the outlet channel (figure 6a). We can observe monotonic increase of the mixing efficiency with frequency increase. However, for $f = 1000 \text{ Hz}$ the mixing efficiency decreases dramatically and flow happens to be structured (figure 6b). The mixing efficiency decreases by 35 and 27% at a distance of $D_h$ and $5D_h$, respectively, for $f = 1000 \text{ Hz} \ (\text{figure 6c})$. 

![Figure 6.](image)
Figure 6. The concentration fields – a, b and the mixing efficiency – c, Re = 400

5. Conclusions
The µLIF technique was applied to measure concentration fields and mixing efficiency inside T-shape microchannel for different Reynolds numbers disturbed by external excitation with various frequencies. For all flow regimes studied, mixing enhancement was obtained. For stationary symmetric vortex flow (Re = 120) mixing can be increased up to two times at the excitation frequency $f = 800$ Hz. Significant enhancement can be achieved at the beginning of the outlet channel operating in steady asymmetric regime (Re = 186) by forcing within certain frequency ranges ($f = 500$ Hz, $f = 800$ Hz). Nevertheless, mixing suppression was also observed for two flow regimes (Re = 400, $f = 1000$ Hz) and (Re = 120, $f = 700$ Hz). Non-monotonical response of the flow to the different perturbation frequencies contradicts to previous studies of pulsed flows and means that there are preferable frequency ranges for the flow that probably correspond to the natural instability frequencies.

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6. References
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