Estimation of the flows mixing efficiency inside T-micromixer with an external perturbation for low Reynolds numbers

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Abstract. The flow pattern regimes and mixing quantities in case of an external perturbation for low Reynolds numbers in a T-shape microchannel were studied experimentally using the LIF technique. Formation of a hydrodynamic wave travelling along the outlet channel for the stratified regime was discovered. The wave amplitude is $0.057 \text{W}_{\text{out}}$. The wavelength corresponding to distance between two nearest pits is $3.86D_h$. The change of mixing efficiency between undisturbed and perturbated flows in each of the considered sections is less than 6%. However, the arising of wave causes a decrease in the distance at which the flows are completely mixed.

1. Introduction

Increase of flows mixing efficiency at the microscale devices is major operation in the development of microfluidic systems. Microchannel systems meet a growing demand for a compact device demonstrating high mixing performance which is essential in medicine, biology, chemistry and physics. Production efficiency of such systems as fuel cells providing a long autonomous operation of laptops and microreactors depends on the flow pattern regimes [1, 2] and the mixing efficiency of reagents [3] inside the microchannels. Therefore, development of microfluidic devices with high mixing quality is an important area of research.

The investigation of flow pattern regimes and mixing in channel with smooth walls for different configuration has been carried out. Kockmann et al. [4] showed that a transition between several flow regimes is possible for various Reynolds numbers and microchannel geometries. Soleymani et al. [5], Andreussi et al. [6] carried out numerical simulations which helped to shed some light on critical channel’s characteristics affecting the flow regime change. A Dean vortex arising in the confluence region indicates a transition between the stratified flow and symmetric steady vortex regime.Engler et al. [7] experimentally showed that Dean vortices become non-symmetric with critical Reynolds number $\text{Re} = 150$ for a channel with dimensions of $600\times300\times300 \mu \text{m}$. A pair of non-symmetric vortex structures in the confluence region leads to the engulfment flow regime. Gobert et al. [8] numerically examined an unsteady periodic regime ($\text{Re} = 240$) and stationary asymmetric vortex flow regime ($\text{Re} = 186$) and searched to demonstrate a shift from steady flow regimes to an unsteady one. Comprehensive experimental research of mixing inside a T-microchannel with variation of Reynolds numbers from 100 to 400 was performed by Hoffman et al. [9]. They obtained the velocity and concentration fields using μLIF and μPIV techniques.

One of the most effective ways to increase mixing in the channels is the oscillation superposition to inputs of microchannels. Glasgow et al. [10] presented a variety of dimensionless parameters influencing
mixing efficiency inside the T-microchannel. Although, the numerical simulations were performed in the narrow range of Reynolds numbers (Re < 10) and pulsing frequencies (f < 200 Hz). Erkoć et al. [11] studied the affect of the flowrate pulsation on the vortex formation and mixing efficiency using Computational Fluid Dynamics (CFD) model. Out-of-phase pulsations were performed with frequencies below 200 Hz and for constant Reynolds number Re = 300. They showed that the applied oscillation frequencies close to the natural frequency of the flow promote fully developed and well-ordered vortices along outlet channel. This causes the enhancement of mass transfer and increasing of mixing efficiency. Goullet et al. [12] researched the influence of adding out-of-phase pulsing to a base flow in the inlet channels of T-micromixer for low Reynolds number Re = 0.3 using computational fluid dynamics. They analyzed the dynamics of the flow when two inlets were pulsed at 90° and 180° phase shift. The Strouhal number was 0.094, 0.375, 1.5. Studying the evolution of material lines and contour plot of fluid concentration the authors demonstrated the enhancement of mixing efficiency and distortion of material lines in the outlet channel. The significant influence on hydrodynamics of fluid and pulsed flow structure in the inlet of the outlet channel for Re < 10 was obtained (by Mao and Xu [13]). Karbaschi et al. [14] showed that the flow structure and evolution of the velocity profile shape depended on the external perturbation frequency and channel type significantly. Cheaib et al. [15] studied numerically mixing and fluid hydrodynamic of the pulsed flows in terms of the pulsation amplitude, pulsation frequency, phase angle, channel height, and fluid viscosity for low Reynolds numbers. The pulsation amplitude and frequency proved to have the biggest impact on the flow structure in the mixing channel. Due to pulsation the mixing efficiency experiences spatial fluctuations downstream as well as temporal fluctuation over a pulsation cycle. There is an optimal pulsation frequency below and above which the mixing deteriorates and this optimal frequency depends on the pulsation amplitude and channel width. Researching the pressure disturbance effect on the stream inside T-mixer for Re < 0.24 in the case of convection-dominated diffusion in the outlet channel the best pulsation frequency for maximal mixing condition was determined by Ma et al. [16]. The aim of our paper is demonstration of flow pattern structures arising in case of adding external perturbation to the base stream mixing flow inside T-microchannel and the calculation of the flows mixing efficiency in the case.

2. Experimental setup and measurement conditions

The experiments were carried out in the microchannel setup at Kutateladze Institute of Thermophysics SB RAS. The instantaneous concentration fields of the flow were measured by a laser induced fluorescence (LIF) system based on inverted microscope Carl Zeiss Axio Observer.Z1, consisting of a Nd:YAG laser (wavelength of 532 nm, pulse duration of 10 ns, pulse energy of 25 mJ), CCD-camera (8 bits per pixel, matrix resolution of 2048x2048 pixels) and synchronizing processor. The LIF-system was operated via a computer using “ActualFlow” software. The test section was a T-shaped microchannel made of optically transparent material SU-8 with dimensions of 120×120×240 μm (height H, width of the input channel W_in and width of the output channel W_out) that was mounted on the microscope stage. Distilled water and solution of distilled water with Rhodamine 6G dye dissolving on a molecular level were fed into the microchannel inlets. The concentration of solution was 724 mg/l. An inlet flowrate was preset and controlled by a syringe pump KD Scientific. Adding in-phase pulsing to a base flow in inlet channels was performed using the unique home-made system of flow excitation based on the piezoelectric actuator (the description of the excitation system is given in Kravtsova et al. 2017 [17]). The flow considered is characterized by Reynolds number Re = U_0D_h/ν, where U_0 is the outlet mean flow velocity, D_h = 4S_{mix}/P_{mix} = 160 μm is hydraulic diameter, S_{mix} = H·W_{out} and P_{mix} = 2(H + W_{out}) are the cross-section area and perimeter of the mixing channel, correspondingly, ν is the kinematic viscosity of the flow. The frequency of pulsations, f, was 1000 Hz and determined in the non-dimensional form in terms of the Strouhal number, St = fD_h/U_0. Amplitude of external perturbation was fixed to 100 μm, which corresponds to 3.14·10⁻⁵ m³/s of squeezing volume for f = 1000 Hz.
To calculate the quantitative parameters of mixing on base on concentration fields a calibration curve was constructed. The first step was the acquisition of images at some constants of concentration of solution Rhodamine 6G with liquid in the entire measuring range. The set of specified concentrations of solutions was chosen so to cover the entire range of concentrations in the measurement area during the experiment. For each concentration value 100 images are taken. The next step was the averaging of obtained images. This procedure allows reducing the effects of camera noise and the instability of the laser pulse energy. The background image obtained with natural light is subtracted from the calculated average images. The resulting set of images at various concentrations of solution and distilled water in the stream was used to plot the concentration as a function of brightness at the image point. The construction of a calibration curve to the whole image using the least squares method based on the average intensity values for each image is performed. The calibration curve was supplemented with correction factors for each image point, designed to eliminate the effect of different illumination of the flow areas and obtained by averaging the ratio of the average image brightness to the brightness at the point over all calibration images (see Fig. 2). Then we restored the concentration field from instantaneous images of the stream according to the calibration.

![Figure 1. Sketch of experimental loop.](image)

### Figure 1. Sketch of experimental loop.

**3. Results and discussion**

Experimental investigation of flow in T-shaped microchannel in case of perturbated and undisturbed inlet flows was carried out. The flow with Rhodamine 6G dye is represented by light gray color in plot. The visualization of flow pattern regimes was conducted by LIF methods. The results are shown in Fig. 3. For low Reynolds number (Re < 80) the flows inside outlet channel stream parallel side by side and the liquid-liquid surface is straight line located in central part of channel in case of undisturbed flow regimes. We obtained the arising of travelling wave along central part of the outlet channel in case of

![Figure 2. The average image brightness, $I_0$, against concentration of solution Rhodamine 6G with liquid, $c_{max}$.](image)

**Figure 2.** The average image brightness, $I_0$, against concentration of solution Rhodamine 6G with liquid, $c_{max}$. 
external sinusoidal perturbation. The wave amplitude is 0.057$W_{\text{out}}$. The wavelength corresponding to distance between two nearest pits is 3.86$D_h$. The formation of waves in gas in case of Re = 35 and 105 and the oscillation frequency 1 Hz was indicated by Tu et al. [18]. Also, the waves were presented by Kravtsova et al. [19].

The main indicator of the impact of an external disturbance on the flow is the mixing efficiency. To obtain the mixing quality in cross section of outlet channel we used the following expression [20]:

$$I_m = 1 - \frac{\sigma^2}{\sigma_0^2},$$

where $\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (c_i - \bar{c})^2$, $\bar{c}$ is the average value of the concentration, $\sigma_0^2 = \bar{c}(c_{\text{max}} - \bar{c})$ is maximal root mean square deviation for mixing of liquid with concentration of 0 and $c_{\text{max}}$. Thus, the liquids are completely mixing $I_m = 1$, the liquids are segregated $I_m = 0$. This method allows us to calculate the mixing efficiency in each cross section of the outlet channel.

The mixing efficiency from inlet of outlet channel at every 0.5 hydraulic diameters was calculated. The value of mixing in case of undisturbed flow is marked by the transparent circles. For perturbated flow the mixing quantity was examined for different phases of sinusoidal pulsation in case of $t = 0$ and $t = 0.375$. In plot they are marked by the transparent triangle and transparent square, respectively. The mixing efficiency $I_m$ against hydraulic diameter $D_h$ is shown in Fig. 4.

The mixing efficiency at distance 0$D_h$ varied from 0.12 to 0.14. The mixing grows up to 3$D_h$ and decreases slightly downstream. The change of mixing efficiency between undisturbed and perturbated flows in each of the considered sections is less than 6%.

![Figure 3. The instantaneous concentration fields of stratified regime Re = 70 and evolution of hydrodynamic wave travelling along the outlet channel obtained with shift of time $\Delta t = 0.125$ ms, St = 0.41, $f = 1000$ Hz.](image)

![Figure 4. Mixing efficiency $I_m$ against hydraulic diameter $D_h$. Re = 70.](image)
As it is known, the flow in microchannel with smooth walls is laminar and the longitudinal direction of the dominates in case of low Reynolds number (Re < 80) [21, 22] therefore the mixing between flows is principally diffusive. In microchannels the diffusive mixing is slower compared to convection mixing flows in the channel and Peclet number is large \( Pe = \frac{U_0 \cdot l}{D} > 10^5 \), where \( l \) is distance along mixing channel, \( D < 10^{-9} \) m/s is coefficient of molecular diffusion. Therefore, Stroock et al. [22] suggested using the value, \( \Delta y \), which involved the distance along the channel necessary for mixing flows. When arising travelling wave at liquid-liquid surface the value \( \Delta y \) is determined as \( \Delta y = (\Delta y_{1000} - \Delta y_0)/Pe \), where \( \Delta y_{1000} = U_0 \cdot \lambda_{1000} \cdot x_{1000}/D \), \( \lambda_{1000} \) is the wave length along mixing channel, \( \Delta y_0 = U_0 \cdot \lambda_0 \cdot x_0/D \), \( \lambda_0 \) is the length of liquid-liquid surface which equals \( l \) in this case. The distance of mixing \( \Delta y_{1000} \) can be very large (~1 m) and grow in direct proportion to the value of Pe. The arising of wave causes a decrease in the distance at which the flows are completely mixed (Fig. 5).

![Figure 5. Change of mixing distance with increase of liquid-liquid surface length.](image)

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References
[1] Choban E R, Markovsky L J, Wieckowski A, Kenis P J A 2004 *Journal of Power Sources* **128** (1) 54–60
[2] Jayashree R S, Gancs L, Choban E R, Primak A, Natarajan D, Marko-ski L J, Kenis P J 2005 *Journal of the American Chemical Society* **127** (48) 16758–59
[3] Gradl J, Schwarzer H-C, Schwertfirm F, Manhart M, Peukert W 2006 *Chemical Engineering and Proceedings* **45** (10) 908–16
[4] Kockmann N, Engler M, Foll C 2003 *ASME Proceedings*, Rochester, 911–18
[5] Soleymani A, Yousefi H, Turunen I 2008 *Chemical Engineering Science* **63** (21) 5291–7
[6] Andreussi T, Galletti C, Mauri R, Camarri S, Salvetti M V 2015 *Computers and Chemical Engineering* **76** 150–9
[7] Engler M, Kockmann N, Kiefer T, Woias P 2004 *Chemical Engineering Journal* **101** 315–22
[8] Gobert C, Schwert F, Manhart M 2006 *Proc. ASME Joint U.S.-European Fluids Eng. Summer Meeting*, Miami, *FEDSM2006-98035* 1053–62
[9] Hoffmann M, Rabiger N, Schluter M, Blazy S, Bothe D, Stemich C, Warnecke H-J 2003 *11th Europ. Conf. on Mixing. Bamberg, Germany*, 269–76
[10] Glasgow I, Lieber S, Aubry N 2004 *Anal. Chem.* **76** (16) 4825–32
[11] Erkoc E, Fonte C P, Dias M M, Lopes J C B, Santos R J 2016 *Chemical Engineering Research and Design* **106** 74–91
[12] Goullet A, Glasgow I, Aubry N 2005 *Discret. Contin. Dyn. Syst. April* 327–36
[13] Mao W B, Xu J L 2009 *Int. J. Heat Mass Transf.* **52** (21–22) 5258–61
[14] Karbaschi M, Javadi A, Bastani D, Miller R 2014 *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **460** 355–60
[15] Cheaib F, Kekejian G, Antoun S, Cheikh M, Lakkis I 2016 *Microfluidics and Nanofluidics* **20** (70) 19
[16] Ma Y, Sun C-P, Fields M, Li Y, Haake D A, Churchil B M, Ho C-M 2008 *J. Micromechanics and Microengineering* **18** (4) 45015
[17] Kravtsova A Yu, Meshalkin Yu E, Bilsky A V 2017 *IOP Journal of Physics: Conf. Series* **925** (012020) 5
[18] Tu G, Li W, Du K, Huang G, Wang F 2014 *Chemical Engineering Journal* **247** 125–33
[19] Kravtsova A Yu, Ianko P E, Kashkarova M V, Bilsky A V 2019 *Journal of Visualization* 1–5
[20] Dankwerts P V 1952 *Appl. Sci. Res.* **279–96
[21] Mariotti A, Galletti C, Mauri R, Salvetti M V, Brunazzi E 2018 *Chemical Engineering Journal* **341** 414–31
[22] Stroock A D, Dertinger S K V, Ajdari A, Mezic I, Stone H A, Whitesides G M 2002 *SCIENCE* **295** 647–51