Investigation of unsteady flow regime in a T-shaped channel by means of Time-Resolved PLIF and PIV techniques

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Abstract. T-shaped channels are widely used as micro-mixers in microfluidic systems for chemical and biochemical engineering applications. The mixing efficiency of T-shaped channels relies on three-dimensional flow structure which is dependent on Reynolds number. The most favourable flow regime with relation to the mixing efficiency is an unsteady engulfment flow regime, which has a periodic nature. In the present work, the spatial and temporal scales formed in a T-shaped channel are studied at Reynolds number corresponding to unsteady three-dimensional flow regime. The combination of PLIF and PIV techniques with the high temporal resolution was used in the T-channel cross-sections to investigate the evolution of velocity and concentration fields.

1. Introduction
The increasing demand for efficient, resource-saving, and environmental technologies has led to the development of microfluidics. Microchannel systems are widely used as highly efficient heat exchangers, as well as standard devices in the field of analytical chemistry and biomedical diagnostics. Micromixers are one of the main components of microfluidic systems [1, 2]. T-shaped micromixers are the most effective and easy to manufacture. High efficiency of mixing and mass transfer in T-shaped micromixers has been found in numerical [3] and experimental works [4, 5]. High quality mixing in the T-shaped micromixer is achieved by the formation of a three-dimensional S-shaped flow structure [5-7], which is formed as a result of the loss of flow symmetry [8] and the transition to an asymmetric flow regime (engulfment flow regime) [5]. The engulfment flow regime is characterized by input streams interlacing, resulting in increased interfacial area. This flow structure provides high concentration gradients and, as a result, the mixing quality increases. The onset of the engulfment flow regime is accompanied by a change in the velocity profile in the output mixing channel and depends on the Reynolds number and the channel aspect ratio [5]. The Reynolds number $Re_d$, at which engulfment flow regime occurs, varies from 140 to 160 [5, 9, 10]. To determine the best conditions for effective mixing, the influence of various flow parameters (initial conditions, Re number, geometric parameters of micromixers) on the formation of engulfment flow regime was studied in [5, 11]. It was shown that T-shaped micromixers with symmetric input conditions have the best mixing quality with equal flow rates and ratio of the input channel area to output channel area equal to 1:2. When studying the dynamics of the three-dimensional flow structure in the asymmetric (engulfment) flow regime, it was found that at $Re_d = 260$ according to experiments [9] and $Re_d = 240$ according to numerical simulation [9, 12], the flow at the input to the mixing channel becomes periodic. The Strouhal number which corresponds to the periodical pulsations varies in the following ranges: $St_d = 0.15 – 0.29$ for
Red = 250 – 375 [12]; St d = 0.11 – 0.30 for Re d = 189 – 397 [9]; St d = 0.17 – 0.27 for 245 \leq \text{Re}_d \leq 330 [13]; St d = 0.2 – 0.31 for 253 < \text{Re}_d < 507 [10]. The presence of a characteristic frequency in the flow affects the quality of mixing, which reaches its maximum value in these ranges of Re numbers. The periodic asymmetric flow regime is characterized by periodic merging of three-dimensional vortex structures in the center of a mixing channel [9-10, 13-15]. The study of unsteady three-dimensional vortex structures in a T-shaped channel was carried out using numerical simulation in [7-8, 13-15].

Direct numerical simulation showed that an increase in the mixing quality in the case of an unsteady asymmetric flow regime occurs as a result of the periodic passage of the merged vortex, which is formed when two pairs of counter-rotating vortices merge in the mixing channel. The results of numerical modeling on the dynamics of the merged vortex were confirmed in a recent experimental work [10], according to which the mixing mechanism in the T-shaped channel in an unsteady engulfment flow is determined by the periodic passage of the merged vortex through the mixing channel. A further increase in the Re number is accompanied by a transition to an unsteady symmetric flow regime and a decrease in the quality of mixing.

The majority of works are devoted to the study of the flow structure at small Re numbers that are valuable for microfluidics. Scenarios of the evolution of the flow structure of transition from a vortex symmetric flow regime to an asymmetric engulfment flow regime with the highest mixing efficiency are described. However, there are practically no works on studying the flow structure with a further increase in the \text{Re}_d number and describing the return to the symmetric flow regime. In this paper, we focus on the flow regime under conditions of transition from an unsteady engulfment flow regime to an unsteady symmetric flow regime. To study the three-dimensional flow in the T-shaped channel at \text{Re}_d = 330, the combined PLIF - PIV measuring system described in [16] with a high temporal resolution is used to measure simultaneously the concentration and velocity fields in different cross-sections.

2. Experimental setup

The experimental test section consisted of a T-shaped channel with two input channels with 70 mm length, cross-section h \times h = 5 \times 5 \text{mm}^2 and output channel with 110 mm length, cross-section h \times 2h = 5 \times 10 \text{mm}^2. The Reynolds number \text{Re}_d = \frac{U_0 \cdot d}{\nu}, determined from the hydraulic diameter of the output channel d, was equal to 330, where U_0 is the average flow rate in the output channel and \nu is the kinematic viscosity. The supply of working fluids to the inlet channels was carried out using a double syringe pump, which provided equal flow rates. An aqueous solution of Rhodamine 6G with concentration of 1.25 mg/l and distilled water were used as the working fluids. Fluorescent dye concentration was selected empirically so that the condition of linear dependence of the fluorescence intensity on concentration of Rhodamine 6G was fulfilled. The flow was seeded by polyamide tracers with 5 \mu m diameter and 1.05 g/cm\text{\textsuperscript{3}} density.

Quantitative measurements of the velocity and concentration fields were carried out using the combined PLIF - PIV system, which allows simultaneous measuring of the instantaneous velocity field and concentration field in the selected channel section. The PLIF - PIV system consisted of two high speed PCO.1200 hs CMOS cameras (10-bit image depth, 1280\times 1024 pix.\textsuperscript{2} frame resolution, 12 \mu m pixel size, 500 fps frame rate), SIGMA f/2.8 lenses with 105 mm focal length. The flow was illuminated by double Nd:YLF New wave Pegasus laser (10 mJ pulse energy, 527 nm wavelength, 180 ns pulse duration, 1 kHz pulse repetition). The cameras and the laser were synchronized using POLIS synchronizing processor. The relative positions of the cameras and the laser are shown in Fig. 1. The measurement area was illuminated using a 0.7 mm thick laser sheet, which was introduced into the T-channel through a mirror mounted at 45°. The PLIF camera was installed at right angles to the optical axis of the PIV camera, which was mounted opposite the measuring region. Separation of PLIF and PIV signals was carried out using a dichroic mirror mounted at 45° degrees to the optical axes of the cameras. Also, optical filters with a transmission wavelength of 555 nm and 525 nm, respectively, were installed on the PLIF and PIV camera lenses. The recording frequency of PLIF and PIV images was 333 Hz, which corresponded to the frame delay of 3 ms. The measurements were carried out in
cross-sections indicated in Fig. 1 by numbers 1, 2, 3, located at distances of 2.5 mm, 6 mm, 10 mm from the wall of the inlet channel, respectively. For each section 3000 PLIF and PIV images were recorded. Further a Cartesian coordinate system is used, in which the z-axis was located at the wall of the input channel along the output channel, and the x, y axes form a plane in cross-sections of the output channel.

The calculation of instantaneous and averaged concentration and velocity fields was carried out in the ActualFlow software. The calculation of the instantaneous concentration field was carried out based on the calibration dependence. The calibration dependence calculated for each pixel made it possible to take into account the spatial irregularities of the laser sheet. Calibration was calculated from images obtained by averaging over 500 pre-processed images corresponding to constant concentration values. As a result of processing, 3000 concentration fields with a resolution of about 20 μm per pixel were obtained. The calculation of instantaneous velocity fields was carried out using tracer images, from which the median value obtained from 3000 images was previously subtracted for each pixel. Correlation analysis was carried out using an iterative multigrid algorithm with a continuous displacement of the interrogation area. When calculating the velocity field, four iterations were performed with 50% overlapping, two iterations had a resolution of 64×32 pixels and two iterations had a resolution of 32×16 pixels. As a result of processing, 3000 velocity fields with a resolution of 154 × 77 μm² per vector were calculated.

3. Results and discussion

Fig. 2 shows the visualization patterns and the corresponding quantitative data of the instantaneous concentration and velocity fields. Fig. 2 a-d shows two characteristic flow patterns, symmetric and asymmetric, which occur in the middle plane of the input channels at z = 2.5 mm. The symmetric flow regime is characterized by the presence of two horseshoe-shaped vortex structures, which are displayed in the measurement plane as four vortex structures, the centers of which can be identified on the instantaneous velocity field in Fig. 2b. A similar symmetric pattern realizes in the vortex flow regime (Re<120), as well as for the unsteady symmetric flow regime (Re> 400) and is characterized by the parallel arrangement of the “legs” of the vortex structures in the output channel [8].

An asymmetric flow pattern, which realizes when the flow symmetry is lost and the flow becomes engulfment, is presented. In Fig. 2 c, d, where two vortex structures can be distinguished, whose centers are located on the diagonal of the output channel. In this cross-section, an asymmetric flow pattern realizes mainly, which is also confirmed by the averaged velocity field (not shown). The flow...
patterns in a cross-section located at the beginning of the output channel at $z = 6$ mm are presented in Fig. 2 e, f, where four vortex structures with the symmetric arrangement but with different intensities are identified. The instantaneous flow pattern in the outlet channel at $z = 10$ mm (Fig. 2 g, h) is characterized by the presence of two large-scale counter-rotating vortex structures whose centers are located asymmetrically with respect to the plane of symmetry. The presence of large-scale vortex structures leads to significant mixing enhancement in this section.

The analysis of instant images of the fluorescence showed that the flow in the T-shaped channel at Re number under study is unsteady and is accompanied by the vortex shedding. Evolution of the flow patterns is presented in Figs. 3-6 as a series of successive fluorescence images. The flow patterns in Fig. 3 and Fig. 4 demonstrate the dynamics of vortex structures in the middle plane of the input channels ($z = 2.5$ mm). Fig. 3 a-d corresponds to the vortex shedding in the symmetric regime. At the initial instant of time the vortex structure descends almost vertically (Fig. 3a, b), then it moves horizontally along the lower wall and, as a result of separation (Fig. 3 c, d) the flow returns to the initial symmetric position.
The scenario of vortex shedding in the asymmetric regime differs from the symmetric regime. The main difference is that the vortex structure sheds in the mixing layer between two liquids located in the diagonal plane of the outlet section of the channel (Fig. 4 a-d) and it is accompanied by a change in the angle of inclination of the mixing layer. Vortex structure shedding occurs with a decrease in its slope angle and scale (Fig. 4 b) to vanishing nearby the center of mixing channel (Fig. 4 d). After the vortex structure vanishes, the angle of inclination of the mixing layer increases, and the flow structure goes over to the initial position (Fig. 4 a). In contrast to [10], we did not observe the coalescence of vortex structures in the center of the output channel; perhaps, this can be explained by a small discrepancy between the initial conditions in the channels.

The dynamics of vortex structures at the entrance of the output channel (z = 6 mm) is presented in Fig. 5. a-d. In this cross-section, the only scenario of the vortex structure shedding is implemented, when the vortex rolls vertically downward in the central plane of the outlet channel and moves horizontally along the lower channel wall in Fig. 5 b, c. A descending vortex is replaced by a vortex formed above the interface of the fluorophore – liquid (Fig. 5 a-d, upper left corner), so the flow structure returns to its original position (Fig. 5 a). The dynamics of vortex structures in the cross-section at z = 10 mm is also characterized by periodicity, as a result of which the vortex structure on the left side goes to the right side (Fig. 6 b) and then coalescences with the lower vortex structure (Fig. 6 c); then the flow pattern returns to its original position. The presented images show that this dynamics of the vortex structures is accompanied by a significant mixing of fluorophore with a pure liquid, which is consistent with the results of the works [10, 14].
To analyze the periodicity of the process of vortex structure shedding, shown in Figs. 3-6, the concentration profiles were analyzed. Profiles of normalized fluorophore concentration were plotted at a point located in the center of the studied cross-sections (Fig. 7 a). Concentration profiles present the dynamics of the process and characteristic times of a change in the regime and disappearance of the vortex structures. For measuring planes located in the outlet channel, the shedding time of the vortex structures decreases. Fourier analysis of these velocity profiles made it possible to determine the characteristic frequencies of the vortex structures shedding (Fig. 7 b). The Strouhal numbers $S_{td} = f_{max} \cdot d / U_0$ are found to be 0.18, 0.36 and 0.41 for the cross-sections located at $z = 2.5$ mm, $z = 6$ mm and $z = 10$ mm, correspondingly.

**Conclusion**

In the present work, dye visualization of the flow structure formed in the T-shaped channel was performed, which showed that the mixing of two liquids is characterized by the formation of a complex merged three-dimensional unsteady vortex structure. Scenarios of the vortex structure shedding, which has not been presented previously in the literature, are described based on the analysis of time sequences of fluorescence intensity distributions. The mixing process is periodic in nature, which is determined by the dynamics of the vortex structures. Using the combined PLIF - PIV measuring system with high temporal resolution, quantitative data on the instantaneous concentration distributions and instantaneous velocity fields, as well as on spatial and temporal scales in several cross-sections of the T-shaped channel were obtained. The experimental data obtained broaden the understanding of mixing processes in T-shaped channels and agree with the results of other authors.

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