Micro-PTV technique application to velocity field measurements in immiscible liquid-liquid plug flow in microchannels

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Abstract. The present paper presents the results of micro-PTV technique application to velocity fields measurements in plug flow of immiscible liquids in T-shaped straight and curved microchannels. The data processing algorithms are described; the procedure for velocity circulation assessment was proposed and applied to measure velocity circulation in aqueous plugs at different flow rates. The comparison with micro-PIV technique application results is performed.

1. Introduction
Microfluidic devices are of great interest in the last years due to multiple advantages such as high-intensity heat and mass transfer, small volumes of reagents, the possibility to control local parameters and safety of the processes carried out [1]. Immiscible liquid-liquid flows in microchannels are widely used in chemical and biomedical applications and allow to enhance the outcome of extraction processes and other chemical reactions [2,3]. Plug flow when a series of plugs of one liquid surrounded by liquid film and separated by slugs of another liquid is essential for microfluidic devices because of its unique properties. The circulations inside plugs enhance mixing and increase mass transfer through the dimeric interface. There is a need to measure velocity fields inside plugs and assess velocity circulation in order to develop and optimize microfluidic devices. Although Microresolution Particle Image Velocimetry (micro-PIV) has become an established technique for velocity field measurements in microflows since 1998 [4], it has some drawbacks in application to immiscible liquid-liquid plug flow. Due to confinement, the velocity distribution inside plugs has the areas with high velocity gradients which impose constraints on the maximum interrogation area. On the other hand, typically flow seeding density is quite low in microflows which leads to large size interrogation areas or velocity fields averaging. Latter has the meaning only for quasi-stationary flows which is not the case for plug flow. The alternative technique to micro-PIV is Microresolution Particle Tracking Velocimetry (micro-PTV). The technique is based on tracking of individual particles on the image frame rather than the correlation of interrogation areas containing a group of particles; thus it can be applied to the high gradient velocity fields.
In the present work, the micro-PTV technique was applied to velocity field measurements in plug flow of immiscible liquids in T-shaped microchannels. The procedure was developed to assess velocity circulation inside plugs.

2. Experimental setup

Velocity field measurements were carried out in plug flow regime of immiscible liquids in T-shaped straight and curved microchannels. The top view of the microchannels is presented in Figure 1. The width of the inlet channels was 200 μm; the width of the outlet channel was 400 μm while the depth of the channels was equal to 200 μm. The curvature radius of the curved channel was 600 μm. Castor oil was a carrier liquid; distilled water played a role of the dispersed phase. Flow rates of dispersed and carried liquids were varied in the range $0.695 \mu l/min < Q_d < 4.17 \mu l/min$ and $0.695 \mu l/min < Q_c < 8.34 \mu l/min$ by means of KD Scientific double syringe pump. The dispersed phase was seeded by 2 μm fluorescent particles with 0.07% concentration by volume. The scheme of the experimental setup is shown in figure 1. The microchannel was mounted on the Zeiss microscope stage. The velocity measurements were performed at a distance of 8.5 mm from a T-junction and the curved part. The focal plane was set to the central plane of the channel. The flow was illuminated through the microscope lens by double Nd:YAG laser with 532 nm wavelength. The light emitted by particles was directed to a dichroic mirror and captured by a double exposure CCD camera with 4 Mpix resolution. The spatial resolution achieved was 0.8 μm/pixel.

3. Results and discussions

3.1. Velocity field calculation

All calculations were performed using our in-house ActualFlow software, where PTV algorithm was realized. For PTV calculations a pair of tracer images with a short time delay between them is required similarly to PIV. The algorithm detects individual particles at both the first and the second frame and then matches them to obtain the most probable displacement of each particle. The algorithm includes three main stages: particle identification, relaxation algorithm, and result correction. At the first stage – particle identification – a raw image of tracer particles (Figure 2 (a)) is filtered using the Ricker wavelet convolution with a Fourier transform of an initial image. This operation allows to single out characteristic structures and to decrease noise. Further, local maxima at the image are found. A particular pixel is defined as local maxima if it has maximum intensity in the area of $3 \times 3$ pixels around.
Finally, at this stage, we validate if local maxima correspond to tracer particles. To perform this validation, in the vicinity of each local maximum we calculate average intensity $I_{\text{avg}}$ and compare the normalized difference between local maximum intensity $I_{\text{max}}$ and $I_{\text{avg}}$ with some threshold value $P$:

$$\frac{I_{\text{max}} - I_{\text{avg}}}{I_{\text{max}}} \geq P$$

The threshold parameter $P$ should be chosen for particular experimental data because images of tracer particles can differ significantly. Too high values of $P$ can lead to a small amount of identified particles, whereas too small values lead to misidentification and spurious particles. The example of particle identification is presented in Figure 2 (b). In this work, $P$ was varied from 0.9995 to 0.9998.

![Figure 2](image_url)

**Figure 2.** Stages of velocity field calculation using the PTV algorithm: a) a raw image of tracer particles; b) particles found at the image by the PTV algorithm; c) a raw PTV vector field; d) an irregular PTV field after range validation and mask imposition operations; e) a regular velocity field interpolated from PTV data.

The second stage is the relaxation algorithm which estimates first frame particle probabilities of displacing in corresponding particles in the second frame. This algorithm is based on two main principles: maximum particle velocity (or displacement) is defined, and continuity of velocity field is satisfied (local groups of particles moves in the approximately same direction). When the most probable displacement is determined, the corresponding velocity vector is calculated for each pair of particles. A more detailed description of the relaxation algorithm is presented in [5].

At the final stage, the correction of results is performed using the correlation function maximum [6]. Each particle from the second frame is shifted according to the previously calculated displacement and correlation between particle from the first frame, and the shifted particle are calculated. Since a maximum of the correlation function is known, corrections to the initial displacement are made. An example of the resulting irregular velocity field is presented in Figure 2 (c). If spurious or irrelevant vectors appear and it is impossible to eliminate them just by varying threshold value $P$, additional procedures such as image masking or velocity vector range validation should be applied. Irregular field after mask imposition and range validation is shown in Figure 2 (d). Eventually, irregular fields were interpolated into a regular grid using second order local polynomial algorithm for further calculation of derivatives (Figure 2 (e)). Amount of nodes in the grid was approximately equal to the number of vectors in the irregular field. For experiments in this paper typical grid resolution was $8 \times 8 \mu m^2$. 

3.2. Velocity circulation assessment

To assess circulations inside plugs for liquid-liquid plug flow it is convenient to use vorticity fields calculated from velocity derivatives. Often, the PIV algorithm provides unsatisfactory results and resolution of velocity field insufficient to calculate the vorticity field. For instance, this case takes place for serpentine microchannels, where velocities inside plugs have different directions. In Figure 3 the comparison between vorticity fields obtained from PIV and PTV data is presented. PIV velocity field was calculated using 64×64 pixel grid without overlapping, further refinement of the grid was impossible due to initial image quality and insufficient flow seeding. As can be seen in Figure 3, the vorticity field obtained from PIV data, even the main vorticies in the front part of the plug are resolved poorly. Besides, small values of velocity vectors near the plug boundary introduce significant error into the resulting vorticity field. By comparison, using interpolated PTV results, adequate vorticity field can be calculated even for a curved channel.

![Figure 3. Comparison between PIV (left) and PTV (right) measurements of velocity and vorticity fields inside the aqueous plug in the curved microchannel.](image)

For the assessment of velocity circulation inside plugs, the following procedure has been developed. From calculated velocity derivatives, the vorticity component, directed orthogonally to the measurement plane, were obtained. The total circulation in the plugs was calculated from vorticity distributions using the following equation:

\[
\Gamma = |\Gamma_+| + |\Gamma_-| = \int\int_S \left| \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right| \, dx \, dy \approx \sum_{i=0}^{N} |\omega_z| \, S_i
\]

We approximated the area integral with the sum of the z-th component of vorticity \(\omega_z\) multiplied by the cell area \(S\) for each cell in the circulation areas. Circulation areas were defined as areas with vorticity values greater than 25% of the maximum for a given plug. It allowed us to eliminate areas with low vorticity from consideration. To take into account the circulation regions with both positive and negative vorticity values, the values of \(\omega_z\) were taken in absolute value.

Using the described approach to the total circulation assessment experiments with castor oil - water plug flow in the straight microchannel were conducted. The plot of the total circulation versus \(Ca_{bulk}Q_d/Q_c\) parameter, where \(Ca\) is the capillary number, is shown in figure 4. Total circulation depends linearly on \(Ca_{bulk}Q_d/Q_c\). This result is in agreement with the work [7], where \(Ca_{bulk}Q_d/Q_c\) was shown to describe plug shape and velocity fields inside aqueous plugs in castor oil.
4. Conclusion
In the present study, micro-PTV technique was applied to velocity field measurements in plug flow of immiscible liquids in microchannels. Two types of microchannels were used: straight T-shaped microchannel and curved T-shaped microchannel. Velocity field and velocity circulation calculation procedures were described. It was demonstrated that the micro-PIV technique does not take satisfactory results for velocity circulation assessment in case of curved plug due to the restriction of seeding density on the minimum size of the interrogation area. Velocity circulation at different flow rates was calculated in the T-shaped microchannel, its linear dependence on $Q/\dot{Q} \cdot Ca_{bulk}$ was shown.

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5. References
[1] Squires T M and Quake S R 2005 Microfluidics: Fluid physics at the nanoliter scale Rev. Mod. Phys. 77 977–1026
[2] Šalić A, Tušek A and Zelić B 2012 Application of microreactors in medicine and biomedicine J. Appl. Biomed. 10 137–53
[3] Xu C and Xie T 2017 Review of Microfluidic Liquid–Liquid Extractors Ind. Eng. Chem. Res. 56 7593–622
[4] Santiago J G, Wereley S T, Meinhart C D, Beebe D J and Adrian R J 1998 A particle image velocimetry system for microfluidics Exp. Fluids 25 316–9
[5] Theunissen R, Stitou A and Riethmuller M L 2004 A novel approach to improve the accuracy of PTV methods 12th Int. Symp. Appl. Laser Tech. to Fluid Mech. Lisbon, Port. 12–5
[6] Akhmetbekov Y K, Markovich D M and Tokarev M P 2010 Study of the PTV method with individual particle correlation correction Comput. Technol. 15 57–72
[7] Kovalev A V, Yagodnitsyna A A and Bilsky A V 2018 Flow hydrodynamics of immiscible liquids with low viscosity ratio in a rectangular microchannel with T-junction Chem. Eng. J. 352