Effect of the inlet flow rate ratio on liquid efficiency in a T-shaped micromixer at low Reynolds numbers

A Yu Kravtsova, M V Kashkarova, P E Ianko, A V Bilsky and Y V Kravtsov

Kutateladze Institute of Thermophysics, Siberian Branch of the Russian Academy of Sciences, 1, Lavrentyev Ave, 630090 Novosibirsk, Russia
Department of Physics, Novosibirsk State University, 2, Pirogov Str, 630090 Novosibirsk, Russia

E-mail: Kravtsova.Alya@gmail.com

Abstract. The effect of the ratio of inlet flow rates on the flow structure and efficiency of liquid mixing in a T-shaped micromixer was studied at low Reynolds numbers using the method of particle image velocimetry and laser-induced fluorescence techniques. It was found that under the stationary flow regimes, the maximum efficiency of liquid mixing is 0.86 at Re = 186 and inlet flow ratio (R) of 1. The maximum dimensionless value of the longitudinal component of the mean flow velocity (up to 2.0) is achieved for the cases with the smallest and largest inlet flow ratio, that is, at R = 0.03 and R = 1.

1. Introduction

The limited resources of fossil fuels stimulate the search for new sources of energy and technologies for its production. A special place among these alternative technologies belongs to fuel cells, which allow converting the chemical energy of a substance into electricity. The most promising of them are micro-sized membraneless fuel cells of the T-configuration. The productive operation of such devices requires a stationary flow inside the element and liquid mixing only due to diffusion. Accordingly, to increase the productivity of such elements, various flow regimes are searched, including those with a change in the ratio of inlet flow rates of reagent aimed at an increase in the efficiency of diffuse mixing.

By now, various flow regimes in micron-sized channels and their effect on mixing efficiency at equal inlet flow rates and different Reynolds numbers have been studied [1-3]. Thus, it was found that the generation of Dean vortices in T-shaped microchannels leads to the formation of a transverse flow in the outlet channel, but does not significantly affect the mixing of reagents [4]. At Re = 145, symmetry in the flow is lost and mixing efficiency increases [3]. At Re = 240 and equal inlet flow rates, the stationary flow regime in the outlet channel of a rectangular cross-section is replaced by a non-stationary flow, and this leads to an increase in the mixing efficiency [5]. To study the flow in microchannels with equal inlet flow rates, Hoffman et al. [6] used the methods of laser-induced fluorescence and particle image velocimetry. The mixing efficiency was estimated using the obtained concentration fields and intensity of segregation by Dankwerts [7]. Various flow regimes were also established for the modified geometry of the channel. Chakraborty et al. have distinguished three mixing regimes when studying the flow in the T-shaped micromixers on rotating platforms [8]. Ansari et al. [9] found that in a T-mixer with the inlets located at different heights there are the flows that cause mixing at lower Reynolds numbers as compared to a conventional T-mixer. Rahimi et al. [10]
determined that the mixing efficiency increases with an increase in the inlet flow ratio and with a decrease in the angle of convergence of the inlet flows. They showed that the mixing efficiency depends also on the channel geometry and velocity of the output flow. At the same time, detailed information on the effect of inlet flow rates on the liquid flow in the outlet microchannel remains extremely limited. The work aims at establishing the features of the liquid flow in a T-shaped micromixer at low Reynolds numbers, depending on the ratio of the inlet flow rates.

2. Experimental setup and measurement conditions

Flow hydrodynamics in a microdimensional channel with different inlet flow ratios was studied experimentally at the Institute of Thermophysics SB RAS. The working channel is a T-shaped microchannel with dimensions of 120×120×240 μm made of optically transparent material SU-8. The inlet flow rate is organized by a syringe pump. The mixing process in the microchannel is achieved by changing the ratio of inlet flow rates. Since the geometry of the T-microchannel is symmetrical, we assume that the flow rate in the left inlet channel (Q₁) is less than the right inlet flow rate (Q₂): Q₁ < Q₂. The inlet flow rate ratio is defined as ratio R: R = Q₁/Q₂. The values of R determined in this way are always less or equal to 1. The working liquid is distilled water. The Reynolds number is determined as Re = U₀ · D₀/ν for the mixing channel, where D₀ is the hydraulic diameter of the outlet channel; U₀ is the bulk flow velocity; ν is the kinematic viscosity of the flow, whose value is taken depending on room temperature. The hydraulic diameter of the outlet channel is 160 μm. The experimental study was carried out at the Reynolds numbers in the outlet channel varying in the range from 3 to 186. To visualize the flow regimes in the outlet channel, the laser-induced fluorescence techniques (LIF) consisting of pulsed Nd:YAG laser (wavelength of 532 nm, pulse duration of 10 ns, pulse energy of 25 mJ), CCD camera (8 bits per pixel, resolution of 2048 × 2048 pixels), and synchronizing processor was used (Kravtsova et al. 2019 [11-12]). As a result, the instantaneous flow images were obtained. The concentration field was restored from instantaneous images of the stream according to the calibration (Kravtsova et al. 2020 [13]). The error in obtaining the concentration field is less than 2%. The mixing efficiency was calculated based on the instantaneous concentration fields obtained by the LIF method in each cross-section of the outlet channel using the following expressions [7]:

\[ I_M = 1 - \frac{\sigma}{\sigma_0} \]

\[ \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (c_i - \bar{c})^2 \]

\[ \sigma_0^2 = \bar{c}(c_{\text{max}} - \bar{c}) \]

where \( I_M \) is the value of mixing, \( \sigma_0^2 \) is the maximum standard deviation for mixing the liquid with a concentration of 0 and \( c_{\text{max}} \), where \( c_{\text{max}} \) is the maximum concentration of dye rhodamine 6G, \( c_{\text{max}} = 362 \) mg/l. Thus, the liquids are completely mixed at \( I_M = 1 \) and separated at \( I_M = 0 \).

The flow velocities were measured by the method of particle image velocimetry (PIV) consisting of a two-pulse Nd: YAG laser (wavelength of 532 nm, pulse duration of 10 ns, pulse energy of 25 mJ), whose light was sent to the microscope using an optical fiber, CCD-camera (color depth of 8 bits, matrix resolution of 2048×2048 pixels), and a synchronizing processor. The PIV system was controlled by a computer employing ActualFlow software. During PIV measurements, tracer particles coated with a fluorescent dye (average size of 2 μm) were added to the flow of the working liquid.

For each set of experimental conditions, 5000 pairs of double images were collected. Velocity fields were calculated using an iterative cross-correlation algorithm with continuous window shift and deformation and a 50% window overlap. Subpixel interpolation of the cross-correlation peak was carried out at three points using a one-dimensional approximation by a Gaussian function. In order to have a relatively large dynamic range (the difference between the maximum and minimum velocities), the size of the initial computational domain was 32×128 pixels. The error in measuring velocity was 1% when the tracer was offset by 6 pixels. The calculated velocity vectors were filtered in two stages:
validation by the signal-to-noise ratio with a threshold of 2, and adaptive median filtering with a region size of 7×7.

3. Results and discussion

To identify the effect of the ratio of inlet flow rates on the hydrodynamics of the liquid flow in the outlet microchannel, instantaneous concentration fields were visualized (Fig. 1). Based on the data obtained, several flow regimes were identified in the T-type channel at low Reynolds numbers with the \( R \) ratios ranging from 0.03 to 1. Partial penetration of the flow into the opposite inlet channel with the formation of vortex structures was discovered for the inlet flow rate ratio \( R = 0.03 \) (Fig. 1a). Rotation of oppositely directed vortices around their axes in the inlet channel leads to flow instability in the outlet channel and does not significantly affect the mixing efficiency. For the inlet flow ratios of 0.21 and 1, a streaks structure appears (Fig. 2b, c). In these cases, the flow inside the outlet channel is stationary. The mixing efficiency is 0.4 for \( R = 0.21 \) and 0.86 for \( R = 1 \).

![Figure 1. Instantaneous concentration fields for Re = 186 at (a) \( R = 0.03 \); (b) \( R = 0.21 \); (c) \( R = 1 \).](image)

In cases of efficient mixing, the highest longitudinal components of the pulsations of the liquid flow velocity in the outlet channel (at distance 1\( D_h \)) were noted. In the central part of the channel, their dimensionless value can reach 0.2–0.4; in the near-wall part, it is fixed up to 0.8. For small Reynolds numbers, the mean flow velocities differ slightly for the considered inlet flow ratios both in the transverse and longitudinal cross-sections. The profile of the longitudinal component of the mean flow velocity at distance 1\( D_h \) from the inlet to the mixing channel is characterized by some features. As known, for ratio \( R = 1 \), the profile of mean flow velocity has three turning points. For \( R = 0.21 \), the profile of the longitudinal component of the mean flow velocity is asymmetric (Fig. 2); its dimensionless values vary from 0\( U_0 \) in the inlet channel with a lower flow rate to 1.5\( U_0 \) in the channel with a higher flow rate. We detected only one turning point and steady growth of velocity value. For ratio \( R = 0.03 \), the longitudinal component of the average flow velocity is characterized by minimal and even negative values in the corresponding channel, which is associated with the formation of a stagnant zone near the front part of the outlet channel.
Figure 2. Longitudinal component of the mean flow velocity at distance 1Dh from the inlet to the mixing channel: R = 0.03; R = 0.21; R = 1.

Conclusions
At low Reynolds numbers, the ratio of inlet flow rates varying from 0.03 to 1 affects the nature of the liquid flow in the outlet microchannel in different ways. The optimal conditions for liquid mixing in a stationary flow inside the outlet T-microchannel are formed at Re = 186 and R = 1. The mixing coefficient under these conditions reaches 0.86. For ratio R = 0.21, the profile of the longitudinal component is asymmetric. For ratio R = 0.03, the longitudinal component of the average flow rate is characterized by minimal and even negative values, which implies that a vortex structure is formed near the outlet channel wall.

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