Examination of the dominant factor affecting the mixing in the microchannel

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Abstract. The effect of the input flow-rate ratio and the Reynolds numbers in range from 10 to 300 on the mixing of liquids in a T-type micromixer was examined. Linear trends of mixing efficiency change on the ratio of input flowrates and Reynolds number are approximated. The most effective mixing (the mixing coefficient reaches 0.86) was obtained at Reynolds numbers 186 and 300 and the input flowrate ratio \( R = 1 \). It is determined that with equal input flow rate ratio, as the Reynolds number increases from 10 to 300, the mixing efficiency rises sharply: from 0.2 to 0.8 (for \( 0.5 < R < 1 \)). Variation of the ratio of input flowrates at low Reynolds numbers in the range from 10 to 120 can lead to a significant increase in the mixing of liquids (Re = 47, the growth mixing from 0.22 to 0.67). With Reynolds numbers 186 and 300, as the input flowrate ratio increases from 0.1 to 1, the mixing ratio rises from 0.25–0.30 to 0.85–0.90.

1. Introduction
Efficient and resource-saving systems based on microelectromechanical technologies becomes increasingly important. Since microchannel mixers work, as a rule, in laminar flow regimes the task of increasing the mixing efficiency is relevant. For effective use of micromixers, it is necessary to study the mixing of liquids in them when changing the flow regime parameters including Reynolds numbers and the ratio of input flowrates.

The occurred flow regimes in micronsized channels and their effect on the mixing efficiency at a ratio of input flow rates equal to one for various Reynolds numbers are presented by Wong et al. [1], Gobert et al. [2], Mariotti et al. [3] and others. Engler et al. in 2004 [4] showed that the arising of Dean vortices (Re > 80) in the outlet channel of a T-type microchannel leads to the appearance of a transverse flow however does not significantly affect the mixing of liquids. At a Reynolds number of 145 the Dean vortices lose their symmetry and the mixing efficiency increases significantly [5, 3]. A change in the flow regime in the outlet channel of a T-micromixer with a rectangular cross section from stable to unsteady at identical input flowrates occurs at the Reynolds number equal to 240, and, as a consequence, leads to a significant increase in the mixing efficiency [6]. Chakraborty et al. [7] studied liquid flow in T-shaped micromixers on rotating platforms. They identified three mixing regimes based on different flow behavior. Diffusion mixing was obtained for low flowrates. Increasing the rotation speed of the platform allows to growth of the mixing efficiency reagents inside the
micromixer. Ansari et al. [8] analyzed vortex flow in a T-shaped mixer with inlets located at different heights. In such a mixer, flows are formed that cause mixing at lower Reynolds numbers, in comparison with a simple T-shaped mixer, due to the formation of a vortex at the inlet of a rectangular microchannel, which, developing downstream, increases the area of separation between liquids in the outlet channel and when visualizing this regime in the central part of the channel, the appearance of thin stripes - "streaks" is observed. This increases the mixing efficiency. Rahimi et al. [9] investigated the influence of the channel confluence angle, flowrate and input flowrate ratio on mixing efficiency in channel with circular section for low Reynolds numbers. They found that the mixing efficiency increases with an increase in the flow ratio and with a decrease in the confluence angle. They demonstrated that mixing efficiency also depends on channel geometry and outlet flow. However, no generalization on the influence of flow hydrodynamics on mixing in a broad range of Reynolds numbers has been given.

The purpose of this work is to determine the dynamics of the efficiency of liquid mixing in a T-shaped micromixer depending on the change in the ratio of input flowrates and Reynolds numbers.

2. Experimental conditions
Experimental investigation of fluid flow in microscaled channel was carried out using laser induced fluorescence system. The working channel is a T-type device made of optically transparent SU-8 material with square section of inlet arms and rectangular cross-section of outlet one. It is dimensions of 120×120×240 microns. The KD Scientific88 syringe pump with dual independent outlets provides continuous of the fluid flow to the microchannel inputs. The experimental investigation was carried out in two settings: the fluid flow through the microchannel was examined at a fixed output flowrate and a change in the ratio of input and next at a fixed ratio of input flowrates and a change in the output. The liquid flowrate at the inlet ranges from 0.39 ml/hour to 202 ml/hour. The ratio of input flowrates R was defined as the ratio of a smaller input flowrate to a larger one, i.e. \( R = \frac{Q_1}{Q_2} \), \( Q_1 < Q_2 \). The Reynolds number is determined as \( \text{Re} = \frac{U_0 \cdot D_h}{\nu} \) for the mixing channel, where \( D_h \) is the hydraulic diameter of the outlet channel; \( U_0 \) is the bulk flow velocity; \( \nu \) is the kinematic viscosity of the fluid, whose value is taken depending on room temperature. The hydraulic diameter of the outlet channel is 160 \( \mu \)m. The Reynolds number was varied from 10 to 300. Distilled water was the working liquid.

The laser induced fluorescence (LIF) method was used for visualization of flow regimes in the working channel. For one inlet arms was fed with distilled water, the second dye solution of rhodamine 6G. The concentration of the solution of rhodamine 6G was 362 mg/l. The flow inside the working area illuminated by an Nd: YAG laser (wavelength 532 nm, pulse energy 25 MJ) for a short period of time equal to 10 ns, which allows recording instantaneous flow patterns. The light reflected by the rhodamine 6G dye in the red wavelength range registered by a CCD camera (8 bits, the resolution of the matrix is 2048x2048 pixels). The system was controlled by a computer with ActualFlow software using synchronizing processor [10, 11]. The resulting images is an instantaneous in time visualization plots.

To calculate quantitative mixing parameters using a calibration curve based constructed on concentration fields. The first step is to obtain images at certain constants of the concentration of the 6G rhodamine solution over the entire measurement range. The set of solution concentrations selected to cover the entire range of concentrations in the measurement area during the experiment. 100 images were taken for each concentration value. The next step is averaging the resulting images. The background image obtained in natural light subtracted from the calculated average images. The resulting set of images at different concentrations of solution and distilled water in the stream used to construct the concentration dependence on the brightness at the image point. The calibration curve for the entire image constructed using the least squares method based on the average intensity values for each image. The calibration curve supplemented with correction coefficients for each image point, designed to eliminate the effect of different illumination of the flow areas and obtained by averaging the ratio of the image brightness to the brightness at the point across all
calibration images. The calibration curve approximated by a polynomial function of the second degree. Then the concentration field restored from instantaneous images of the flow. To calculate the mixing efficiency in each section of the output channel, a concentration profile is constructed and the mixing evaluated using the Dankwerts expression [12]:

\[ I_M = 1 - \frac{\sigma}{\sigma_0} \]
\[ \sigma^2 = \frac{1}{N} \sum (c_i - \bar{c})^2 \]
\[ \sigma_0^2 = c(c_{\text{max}} - \bar{c}), \]

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

3. Results

The efficiency of mixing liquids in the outlet channel of a T-shaped microdevice depends on both the Reynolds number and the input flowrate ratio. To answer the question of which one is dominant in mixing, let's briefly consider several linear trends of proportionality between one of the given factors and the mixing coefficient (figure 1).

![Figure 1. Mixing efficiency against (a) Reynolds number, (b) Flowrate ratio.](image)

For small input flow ratios (\( R = 0.12 \)), the proportionality between the change in the Reynolds number and the dynamics of mixing efficiency is very weak. So, for \( R = 0.12 \), the decrease in the mixing coefficient in the range of Reynolds numbers from 10 to 300 is 0.015. Starting from the Reynolds number 120, the inlet fluid supplied to one of the arms flows into the opposite inlet channel, which, as shown in figure 1a, leads to a sharp decrease in the mixing efficiency in the case of \( \text{Re} = 120 \) and its further gradual growth with an increase in the Reynolds number. In the range of \( R \) ratios from 0.2 to 1, the dependence of the mixing efficiency on the dynamics of the Reynolds number becomes more pronounced as the ratio of \( R \) to 1 approach. As the Reynolds number increases from 10 to 300, the mixing efficiency grows from 0.36 to 0.47 at \( R = 0.25 \) and from 0.38 to 0.55 at \( R = 0.36 \). The difference between the coefficient values is 0.11 and 0.14 for \( R = 0.25 \) and 0.36, respectively. At \( R = 0.73 \), the mixing efficiency increases from 0.39 to 0.63 when the Reynolds number rises from 10 to 300; the absolute increase reaches 0.24. At \( R = 1 \), the mixing efficiency increases from 0.2 to 0.87 as the Reynolds number grows from 10 to 300. The absolute increase in the coefficient reaches 0.67. This change is the highest among all the input flowrate ratios considered.

For fixed Reynolds numbers at 10 and 120, the dependence of the mixing coefficient on the dynamics of the input flow ratio is poorly expressed, the increase in the mixing efficiency is 0.02 and 0.21, respectively (figure 1b). At \( \text{Re} = 186 \), as the ratio of input flowrates increases, the mixing efficiency rises from 0.18 to 0.87. Changes in the values of the mixing coefficient in both cases reach
0.69. The linear trends for Re = 300 are similar to the linear trend for Re = 186, from which we can conclude that for both Reynolds numbers a change of the ratio of input flow rates can significantly affect the results of fluid mixing. Special attention should be paid to the influence of the ratio of input flow rates on the mixing efficiency at the Reynolds number of 47. The change in the mixing efficiency is significant. The maximum value is reached for R = 0.25 and is 0.67. The absolute increase in the coefficient reaches 0.57. With a further increase in the ratio of input flow rates the mixing efficiency decreases and at R = 1 it becomes small 0.24. It can be concluded that changing the ratio of input flow rates, especially at low Reynolds numbers, can significantly change the efficiency of the micromixers and microdevices.

Comparison of proportionality trends and absolute values of mixing coefficients change allows us to conclude that variation of the ratio of input flow rates at low Reynolds numbers in the range from 10 to 120 can lead to a significant increase in the mixing of liquids. In the case of large Reynolds numbers and ratios of input flow rates, the dominant trend is more difficult to distinguish; it is shown that the mixing ratio increases markedly at Reynolds numbers from 186 to 300 and with a growth in the ratio of input flow rates.

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