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Influence of perturbance frequency on intensity of mixing of fluids in microchannel devices

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Abstract. Influence of perturbation frequency on mixing flow velocity and the varying flow structure in T-shape microchannels are investigated using laser induced fluorescence. The external disturbances of flow are created excitation system based on the piezoelectric actuator. Several increases in mixing efficiency were common to all regimes, but also some different features, were observed. For the stationary vortex flow regime, we obtained a decrease in mixing efficiency of 10% at a frequency of 650Hz. For the stationary asymmetric vortex flow regime, the mixing efficiency increases by 33% and 23% for the frequencies 500Hz and 800 Hz, respectively. For Re=400 and Re=300, the flow structures without disturbance are virtually identical; however, in the case of external influence for the quasiperiodic unsteady flow regime, the mixing efficiency decreases by 22% and 29% at distances of 1 and 5 calibres, respectively, for frequency of 1000 Hz.

1 Introduction

The development of precision technology, both in medical and biological industries, is impossible without the miniaturization of devices. Effective and resource-efficient systems, such as fuel cells, provide a long autonomous operation in different devices (i.e. tablets, laptops, electric cars, microreactors, etc.) and are becoming more important due to their growing use in the manufacture of drugs and regenerative medicine. The performance of these devices depends on the velocity of mixing liquids inside them. Therefore, the development of microfluidic devices with high mixing velocity, throughout the application of external perturbations, is a necessary area of research of hydrodynamic processes in microchannels.

The increase of mixing velocity can be achieved by applying either passive or active perturbations to the flow. The conventional passive methods of increasing the mixing velocity involve decreasing the thickness of the fluid layers by changing the microchannel size ([1], [2]) and extending the contact area with adjacent liquids. To increase the mixing velocity in the microchannel, an excitation of circulations in the flow and a curvature of the flow lines can be used. Engel et al. [3] and Kockmann et al. [4] have discovered that flow in

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microchannels has three flow regimes: layered laminar flow, vortex flow, and stationary asymmetric vortex flow. In the first case, lines of flow move through the channel with minimal distortion. Small vortices form throughout the flow in the case of vortex regime. Appearance of instability in flow leads to destruction of axial vortex symmetry, and we can obtain stationary asymmetric vortex flow. T-microchannels are eminently suitable for fundamental investigations of mixing processes in the convective micromixers. Hoffman et al. [5] were the first researchers to investigate the different flow regimes in T-shape microchannels for various Reynolds numbers. A detailed study of the concentration profile in a microchannel T-type was obtained by Gobert et al. [6]. They used the computational modeling and technique Particle Tracking Velocimetry in their work. Later, Wong et al. [7] presented a detailed study of flow behavior and properties of mixing in microchannel T-type, but this simulation did not provide a complete understanding of convective effects. Dreher et al. [8] have conducted a numerical simulation in the T-channel with rectangular cross section and showed that the best mixing occurs at Reynolds number from 240 to 700. N. Nama et al. [9] have studied the effect of piezoelectric transducer to the flow in the microchannel, in which the liquid has been supplied at different angles. They showed that the propagating waves from the transducer change the structure formed in the liquid and thereby can influence the mixing velocity. Claudio P. Fonte et al. [10], using Computational Fluid Dynamics (CFD) simulation, studied the effect of flow rate pulsations on the dynamics of the flow and mixing efficiency in the T-shape microchannel; however, an experimental confirmation has still not been obtained. Thus, a significant number of studies of flows in microchannels presented in the literature have been made by mathematical methods of numerical simulation. For examination and validation of these models, an experimental investigation of mixing in microchannels is necessary, and we present our results in the following sections.

2 Experimental conditions and measurement techniques

To obtain the characteristics of the flow the method of laser induced fluorescence (micro-LIF) inverted in microscope Carl Zeiss Axio Observer.Z1 was used. A T-shaped microchannel made of optically transparent material SU-8 with dimensions of $120\times120\times240$ μm (height, width of the input channel and the width of the output channel) was mounted on the microscope stage. Distilled water and a solution of distilled water with the dissolving on a molecular level Rhodamine 6G dye were fed in microcannel. The concentration of the solution is 15mg/l. A flow rate of fluid in the T-microchannel is defined by a syringe pump KD Scientific company with two outputs. A mercury lamp with light filter is used for illumination of the flow in channel. Filter allocates the light with a wavelength of 532 nm, which corresponds to the maximum of spectrum absorption for Rhodamine 6G dye. The dye emitted light in the red wavelength range via the dichroic mirror radiation is directed to a CCD camera with space resolution of 2048×2048 pixels. The resulting images are operated via a computer using "Actualflow" software. The experimental facility is shown in Figure 1.

To create the external disturbances of flow with different frequency, unique excitation system of the flow based on the piezoelectric actuator was mounted (Figure 1). The free running of the piezoactuator with a minimum 1kN preload and the maximum voltage 150V is 150 μm. The system creates an in-phase variable flow rate to both inputs of the T-shaped microchannel. The piezoelectric actuator deforming with predetermined frequency and amplitude passes the perturbation in the flow through the rod by direct mechanical contact with the actuator.

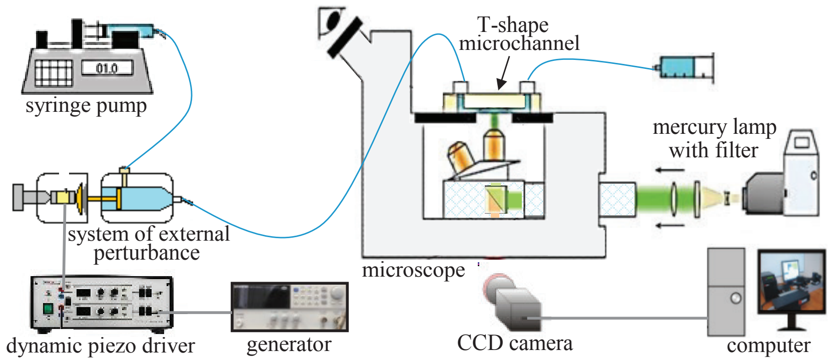

Fig. 1. Sketch of experimental setup

3 Results

Experimental study of influence of the perturbation frequency on the process of mixing flow velocity in a microchannel T-type and the flow structure were examined. The experiments were carried out for Reynolds numbers Re = 120, 186, 300, 400. The system of external perturbance was generated the flow pulsation in the same phase on both inputs of microchannel with the frequency, *f*, range from 0 Hz to 1000 Hz with step 100 Hz. The sampling frequency of measurements was increased four times (step of the measurements was 25 Hz) in region of greatest change of the mixing efficiency (400 Hz to 800 Hz).

The mixing efficiency was calculated for each frequency of disturbance. To calculate the mixing efficiency, M, in T-channels the Dankwerts segregation intensity was used. Mixing efficiency was calculated on basis of concentration fields obtained the micro-LIF method at a distance of 1 and 5 calibers from the entrance of the mixing channel for each flow regime with and without superimposed pulsations.

The first series of experiments are presented for the stationary vortex flow regime Re = 120 (Figure 2a). We can see two symmetrical vortices on this regime which are called the Dean vortices. In Figure 2a the mixing efficiency increases in diapason of frequencies from 0 Hz to 500 Hz at a distance of 1 caliber from the entrance at 6% and at a distance of 5 calibers at 12%. At a further increase of the frequency of the external influence of up to 650 Hz the mixing efficiency decrease at 6% at a distance of 1 caliber and 10% 5 calibers relative to the undisturbed flow. Further increasing the frequency leads to a continuous growth of the mixing efficiency. It becomes maximum by a frequency 1000 Hz and increase by 13% and 16% at a distance of 1 and 5 calibers, respectively. According to the visualization of flow mixing efficiency increases significantly.

For stationary asymmetric vortex flow regime Re = 186 (Figure 2b) the mixing efficiency increase by 33% with raise frequency from 0 Hz to 500 Hz at a distance of 1 caliber from the entrance in working channel. A further increase of the frequency of the external perturbation up to 650 Hz leads to a decrease in the mixing efficiency however it is greater by 10% then in case of undisturbed stream. The mixing efficiency increases by 23% for the growth frequency up to 800 Hz. In the frequency range from 800 to 900 Hz the mixing efficiency decreases to the level of the frequency value for 650 Hz. Next the mixing efficiency increases by 10% up to 1000 Hz. We can observe monotonic increase of the mixing efficiency by 15% for rising frequency of excitation at a distance of 5 calibers from the entrance in working channel.

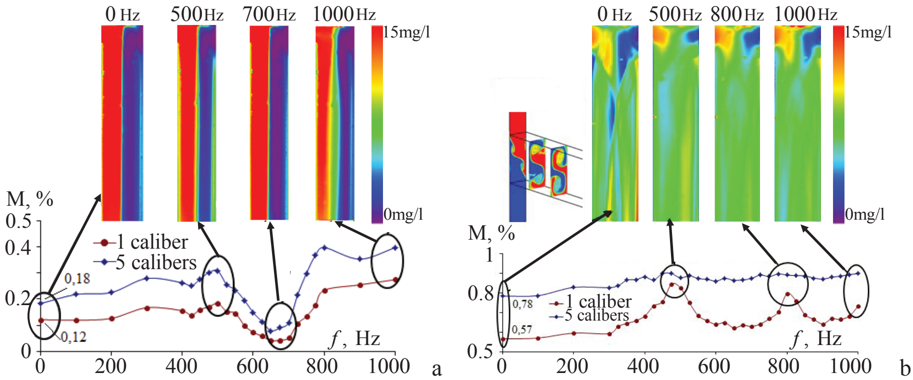

Fig. 2. The mixing efficiency against perturbation frequency for: a - Re = 120, b - Re = 186.

For the periodic unsteady flow regime Re = 300 (Figure 3a) significant influence on the flow structure and mixing efficiency are not detected. With increasing of perturbance frequency the mixing efficiency is virtually unchanged at a distance of 1 and 5 calibers due to availability of the turbulent agitation mechanism in flow, which in turn allows mixing fluids well enough.

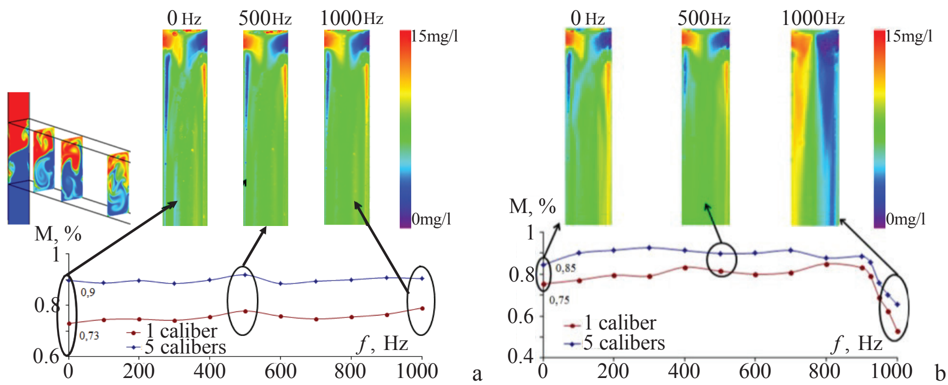

Fig. 3. The mixing efficiency against perturbation frequency for: a - Re = 300, b - Re = 400.

For Re = 400 and Re = 300 the flow structure without disturbance are virtually identical. However, in case of external influence for the quasiperiodic unsteady flow regime (Figure 3b) the mixing efficiency decreases by 22% and 29% at a distance of 1 and 5 calibres, respectively, for frequency of 1000 Hz.

Based on the obtained data we can conclude that in the investigated range of Reynolds numbers the mixing efficiency in T-microchannels1 can be significantly increased by superimposing on the flow of external disturbances of a certain frequency.

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