Numerical investigation of the pulsation frequency of the flow rate effect on the mixing efficiency of the active T-shaped micromixer

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Abstract. Flow patterns and mixing efficiency of fluids with different inlet flow rate pulsation frequencies in T-shaped micromixer were numerically investigated at Reynolds numbers $Re = 100$ and $Re = 180$. The flow rate pulsations were set sinusoidal with different frequencies of 0; 1; 10 and 50 Hz. The relative mixing efficiency means the mixing efficiency of active mixer regarding the mixing efficiency of an identical passive mixer without pulsations at the input; it was considered as the main value. The dependences of such value on the pulsation frequencies were obtained. It was found that active micromixers are much more efficient than the passive ones. Herewith, in the engulfment regime, the mixing efficiency increases twofold regarding the passive mixer, and in the region, before the onset of the engulfment regime, the mixing efficiency increases by about 170 times. In addition, it was found that the increase in mixing efficiency is almost independent of the frequency of pulsations.

1. Introduction

Various ways to improve the performance of micro-mixing equipment have been considered over the past two decades. Since the flow in microchannels is usually laminar, finding ways to increase the mixing performance is necessary for many areas of science and technology. To reach this goal, it is necessary to use a channel with such shape that allows a reduction of the fluids mixing path and an increase in the contact area. According to these principles, the micromixers are classified as the passive and active ones. The literature review shows that passive micromixers demonstrated their effectiveness at relatively high values of Reynolds numbers [1–9]. However, they have also a number of drawbacks: the presence of stagnant zones affecting the mixing process, as well as the geometrically complex micromixer form, which increases the hydraulic resistance. So-called T-type micromixers, in which the fluids flow into two oppositely directed channels, and their mixture moves along the third channel (mixing channel), are broad-reaching among the various forms of micromixers. Such form of micromixer is the most simple to manufacture and quite effective. There are a large number of studies of mixing processes in such microsystems [1, 2, 6-9], however, in these works passive mixing is considered when fluids are fed into the input channels with a constant flow rate without pulsations. At the same time, the mixing technology in micromixers, which is called “active mixing”, is quite interesting. In such a case the flow rate of one or both fluids changes according to some periodic law, thereby creating pulsations. It is clear that the mixing efficiency of two fluids in that mode should be higher as compared to passive mixing. Thus, research in this subject area is
extremely relevant, the results of such investigations will help to create the basis for new technologies for the production of energy-saving systems of transportation, distribution and consumption of heat and the intensification of mixing processes in microscopic systems.

2. Problem statement
A computational study of the mixing efficiency of two fluids in an active T-type micromixer at different pulsation frequencies \( w = 1; 10 \) and 50 Hz for Reynolds numbers \( Re = 100 \) and 180 was carried out in this work. A T-type micromixer consists of two input channels with a cross-section of \( 200 \times 200 \times 1500 \) μm and a mixing channel of \( 200 \times 400 \times 5100 \) μm (Fig. 1). Water with a density of 1000 kg/m\(^3\) and viscosity of 0.001 Pa/s is used as a fluid.

![Figure 1. Micromixer's geometry.](image)

In this work were considered incompressible flows of multi-component fluids, which are described using a hydrodynamic approach based on the solution of the Navier-Stokes equations:

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0 \quad \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla (\rho \mathbf{vv}) = -\nabla p + \nabla \mathbf{T},
\]

where \( \rho \) is the fluid density, \( p \) is the pressure, \( \mathbf{v} \) is the velocity, and \( \mathbf{T} \) is the tensor of viscous stresses, which components are determined as:

\[
\mathbf{T}_{ij} = \mu \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \nabla \cdot \mathbf{v} \right).
\]

Here \( \mu \) is the mixture viscosity and \( u_{ij} \) are the velocity vector components.

The effective viscosity and the density of the mixture are determined through the components mass fraction \( f \) and their effective viscosities \( \mu_{1,2} \) and partial densities \( \rho_{1,2} \), respectively:

\[
\mu = f \mu_1 + (1-f)\mu_2 \quad \rho = \frac{f}{\rho_1} + \frac{(1-f)}{\rho_2}
\]

The evolution of mass concentrations is determined by the next equation:

\[
\frac{\partial \rho f}{\partial t} + \nabla (\rho f \mathbf{v}) = \nabla (\rho D \nabla f),
\]

where \( D \) is the diffusion coefficient.

The software package for computational fluid dynamics “Ansys Fluent” was used to solve the described above equations system.
One of the simplest methods to make the mixing in T-type micromixers active is to set a periodic change in velocity or flow rate at one of the inputs, which is defined as follows: 

\[ Q = Q_0 \cdot (1 + A \cdot \sin(\omega t)), \]

where \( A = 0.2 \). At another input of micromixer, a constant flow rate with a steady velocity profile corresponding to the flow rate \( Q_0 \) is established. The quantitative characteristic of mixing efficiency is the parameter 

\[ M = 1 - \frac{\sigma}{\sigma_0}, \]

where \( \sigma = \sqrt{\frac{1}{V} \int (f - \langle f \rangle)^2 dV} \) is the root-mean-square deviation of the mass fraction of mixture component \( f \) from its average value \( \langle f \rangle \), \( \sigma_0 = \langle f \rangle \cdot (1 - \langle f \rangle) \) is the maximum root-mean-square deviation, and \( V \) is the volume of the computational domain. The Neumann conditions were specified at the outlet of the mixing channel. The no-slip conditions were set on the channel walls. A uniform tetragonal grid consisting of 500000 nodes with a time step of \( 1 \times 10^{-5} \) (the time step was selected on the basis of the Courant–Friedrichs–Lewy (CFL) condition \( \sim 1 \)) was used for calculations. Preliminary calculations showed that such grid detailing is sufficient.

3. Results and discussion

The isolines of the components concentrations at the exit of the mixing channel (Fig. 2) at different pulsation frequencies of 0; 1; 10 and 50 Hz for the Reynolds numbers \( Re = 100 \) and 180 were obtained as a result of the calculations. As it can be seen from Fig. 2, as the Reynolds number increases the vortices are formed in the channel and the contact surface between two media ceases to be flat. This is clearly seen in fig. 2. As the frequency of the pulsations increases, such effect enhances. Because of this the contact area of mixing media increases, which leads to an increase in mixing efficiency.

The relative mixing efficiency (relative to the mixing efficiency for an identical mixer without pulsations at the input) depends on the frequency of pulsations at Reynolds numbers \( Re = 100 \) and 180 is shown in fig. 3. As it can be seen from that figure, as the frequency of pulsations increases the relative efficiency of mixing first increases, and then comes to a plateau. It was found as a result of calculations that active micromixers are much more efficient than the passive ones. Herewith, in the engulfment regime, the mixing efficiency increases twofold regarding the passive mixer, and in the region, before the onset of the engulfment regime, the mixing efficiency increases by about 170 times. In addition, it was found that the increase in mixing efficiency is almost independent of the frequency of pulsations.

![Figure 2. The component concentration isolines at the outlet of the mixing channel at different Reynolds numbers (upper: Re = 100, lower: Re = 180) and at different frequencies of pulsations: a) 0 Hz; b) 1 Hz; c) 10 Hz; d) 50 Hz.](image-url)
Figure 3. The relative mixing efficiency dependence on pulsations frequency: a) Re=100; b) Re=180.

Conclusions
The numerical investigation of the relative mixing efficiency dependence on the frequency of pulsations of the fluid flow rate at the inlet at two different Reynolds numbers Re = 100 and Re = 180 was carried out. The flow patterns and mixing efficiencies for such case were obtained and compared with the same values for the passive mixer. The flow rate at one of the inlets was set constant. At the other inlet, the sinusoidal pulsations of the flow rate were set. The frequencies of pulsations were equal to 0; 1; 10 and 50 Hz. The relative mixing efficiency means the mixing efficiency of active mixer regarding the mixing efficiency of an identical passive mixer without pulsations at the input; it is considered as the main value. The dependences of such value on pulsation frequencies are obtained.

It was found that active micromixers are much more efficient than the passive ones and as the frequency of pulsations increases the relative efficiency of mixing first increases, and then comes to a plateau. Herewith, in the engulfment regime, the mixing efficiency increases twofold regarding the passive mixer, and in the region, before the onset of the engulfment regime, the mixing efficiency increases by about 170 times. In addition, it was found that the increase in mixing efficiency is almost independent of the frequency of pulsations.

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