Mixing in a T-shaped micromixer at moderate Reynolds numbers*  

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In the present work, the regimes of the flow and mixing of fluids in a T-shaped micromixer in the range of the Reynolds numbers from 1 to 1000 are investigated systematically with the aid of numerical modeling. The flow and mixing regimes are shown to alter substantially with increasing Reynolds numbers. Five different flow regimes have been identified in the total. The dependencies of the friction coefficient and mixing efficiency on the Reynolds number are obtained. A sharp increase in the mixing efficiency at a flow transition from the symmetric to asymmetric steady regime is shown. On the other hand, the mixing efficiency slightly drops in the laminar-turbulent transition region. A substantial influence of the slip presence on walls on flow structure in the channel and mixing efficiency has been revealed.  

Key words: microchannels, micromixers, mixing efficiency, hydrodynamic modelling, slip on walls, Dean vortices.  

Introduction  

The mixing of fluids is an extraordinarily important process, which is widely used in various microfluidic devices (chemical micro-reactors, analyzers of chemical and biological substances, systems for drug delivery, etc.). Since the typical times of flow in such devices are very small, one uses special devices — micromixers to accelerate mixing. An immense number of works (see, for example, [1–6] and the literature cited therein) are devoted to the description of the principles of the operation of micromixers and their optimization. One considers, as a rule, laminar flow regimes at small Reynolds numbers, which is usual and typical of microflows [7, 8]. Besides, at relatively high values of the Reynolds number, several new interesting phenomena

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occur in microchannels, which need their investigation from both the fundamental viewpoint and for practical purposes.

Flow regimes in micromixers, which arise at elevated Reynolds numbers, were already studied in several previous works. So the existence of a critical Reynolds number, at which the Dean vortices in the microchannel lose their symmetry, was shown experimentally in the paper [9]. It was found that the critical number \( \text{Re} \approx 150 \) for a channel with sizes 600×300×300 μm. The critical value of the Reynolds number was shown to depend significantly on the channel sizes. The transitional flow regimes (at the Reynolds numbers \( \text{Re} = 300+700 \)) were investigated in the work [10] with the aid of the numerical modelling, however, the mixing processes were not studied. The mixing of two fluids was investigated experimentally and numerically in [11] in the range of the Reynolds numbers from 50 to 1400. The presence of an unsteady periodic regime at some values of the Reynolds number was shown numerically for the first time in the work [12]. The most complete experimental investigation of the mixing in a T-shaped microchannel in different mixer sections was carried out in the work [7] at moderate Reynolds numbers (100+400). The velocity and concentration fields were studied therein with the aid of the \( \mu \)-LIF and \( \mu \)-PIV measurements. The mixing efficiency was measured for the first time.

One should finally note the series of numerical-experimental works [13–15], where, in particular, the computations of some flow regimes in the T-shaped micromixers were done. A number of typical flow regimes were identified, and the flow structure in them was studied. The mixing efficiency was computed. The mixing pattern was compared qualitatively in the computation and experiment. The mixing efficiency distribution over the channel length was computed.

Despite a relatively big number of the works devoted to the study of flows and mixing in T-shaped micromixers at moderate Reynolds numbers, there are in fact still no systematic data on the flow regimes, which take place here, and the mixing therein. The present work is devoted to a systematic modelling of the flow and mixing of incompressible fluids in a T-shaped micromixer at the Reynolds numbers from 1 to 1000. The problem is solved numerically on the basis of the incompressible Navier—Stokes equations.

1. Mathematical model and numerical algorithm

The problem is solved within the framework of the incompressible Navier—Stokes equations:

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

where \( \rho \) is the fluid density, \( p \) is the pressure, \( \mathbf{v} \) is the velocity, and \( \mathbf{T} \) is the tensor of viscous stresses. The viscosity coefficient of the mixture \( \mu \) and its density are defined by the respective relations:

\[
\mu = \sum f_i \mu_i, \quad \rho = \left[ \sum f_i / \rho_i \right]^{-1},
\]

where \( f_i \) is the mass fraction of the \( i \)-component; \( \mu_i \) and \( \rho_i \) are the partial viscosity coefficients and densities. The evolution of mass concentrations is determined by the transfer equation

\[
\frac{\partial \rho f_i}{\partial t} + \nabla \cdot (\rho f_i \mathbf{v}) = \nabla \cdot (\rho D_i \nabla f_i),
\]

where \( D_i \) is the diffusion coefficient of the molecules of the \( i \)-th component.

To solve the above system of equations the algorithm was used, which was developed by the authors using the method of finite volumes for structured multi-block grids [16, 17]. Its application for the description of microflows was shown in the work [18], where the optimization computations of a number of micromixers were also done. In the present work, the results of the hydrodynamical modeling of various flow regimes