FLOW REGIMES OF VISCOUS IMMISCIBLE LIQUIDS IN T-TYPE MICROCHANNEL

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Abstract

A computational and experimental study of the flow regimes of castor and paraffin oils mixture in a T-type microchannel with 200×400 μm cross-section was carried out. The ranges of parallel, slug, droplet, and rivulet flow regimes of the tested mixture were defined. According to the experimental results, a flow regime map was constructed for this mixture depending on Weber numbers. The correlation of the length of paraffin oil slugs on the fluid flow ratio was established. The experimental data were compared with results of numerical simulation. A good agreement between calculation and experimental data was achieved in terms of reproduction of flow regimes, phase boundaries, and slug length.

Keywords: T-type microchannel, castor and paraffin oils mixture, flow regimes, VOF, experiment.

1. Introduction

The microchannel flows of immiscible liquids aroused significant interest in the last decades. Such flows have a number of practical applications. In chemical technologies, the flow of immiscible liquids ensures the continuity and safety of processes providing high efficiency of reactions. This concerns for example, the reaction of extraction [1, 2], nitration [3], and synthesis of nanoparticles [4]. Liquid-liquid microreactors are used in medicine and biomedicine to perform sampling, sample preparation, detection and data processing in integrated model of micro-total-analysis-systems [5, 6]. Microreactors can be used for high throughput screening, drug discovery and testing, cell investigation and single cell experimentation. [7] claim that 50 % of the reactions in the fine chemical or pharmaceutical industry could benefit from a continuous

process based mainly on microreactor technology, and for the majority of reactions (44 %) a microreactor would be the preferred reaction device.

The flows of immiscible liquids in straight channels are characterized by different flow regimes [8-11]. The following regimes were usually observed: droplet flow, plug flow, slug flow, parallel or stratified flow, deformed interface flow, annular and annual droplet flow, and dispersed flow. Besides, in some conditions some occasional flow regions may occur, like annual flow with wavy interface with and without droplets [8], as well as serpentine and rivulet flow regions [9]. The emergence of a certain flow regime is determined by the balance of the system forces. State that the flow regime depends on the balance of inertia and surface tension expressed by Weber number [11]. Take into account the effect of liquids viscosity and use a parameter combined based on the Weber and Ohnesorge numbers. In addition, parameters such as superficial velocity, the Reynolds number [8], capillary number (Ca) [12], Laplace number (La=Re/Ca) [13], as well as a combination of numbers $Re^{0.2} We^{0.4}$ [13] were used to construct flow regime maps in order to generalize the results and to predict the existence of a particular flow regime.

However, for practical applications, not only the regime itself is important, but also hydrodynamic characteristics of the flow, which determine the intensity of heat and mass transfer processes in such systems. For the slug flow regime it is the slug velocity, its length, and the fluid circulation inside the slug. For the slug length, the empirical formula was proposed by [15], which later was developed in [16-20].

The slug velocity is linearly dependent on the total velocity of phases [9, 21], with a proportionality coefficient, which depends on the thickness of the carrier liquid film, emerging between the slug and the wall. A review of current works on the hydrodynamic aspects of the slug flow regime can be found in [22].

Numerical simulation of such flows is carried out as a rule using direct numerical simulation (DNS) methods with tracking the free surface (Volume of Fluid method) [23-25]. It should be noted that such objects require accounting forces at the contact line. Otherwise, the calculation may result in inadequate flow patterns [26, 27]. An overview of methods and publications on numerical simulation of two-fluid flows can be found in [28-29], in particular, notes the lack of works on the numerical investigation of parameters such as film thickness, pressure loss, and heat transfer for two-fluid flows in different types of channels.

The works currently available in the literature are limited to numerical simulation fluids, one of which (water) has significantly lower viscosity than the other (oil). In the present work, a

computational and experimental study of flow regimes in the T-shaped microchannel of paraffin and castor oils mixture with high viscosity was carried out for the first time.

2. Experimental technique

The experiments were conducted in T-type microchannels made of polymer SU-8 by microLIQUID company (Spain). No special treatment of the channel surface to make the surface hydrophilic or hydrophobic was performed. The dimensions of the inlet channels cross-section were 200x200 μm, of the outlet channels cross-section - 200x400 μm that corresponds to the hydraulic diameter of 267 μm. The length of the inlet channel was 11.5 mm while the outlet channel was 22.5 mm long. The microchannel was fixed on the object table of Zeiss Axio Observer.Z1 inverted microscope with a 5x lens (with numerical aperture equal to 0.12) and was illuminated by a built-in halogen lamp. To visualize the flow regimes, a high-speed pco.1200 hs camera was connected to the microscope. The imaging frequency was varied within the range from 5 to 150 Hz depending on the flow velocity. The regimes were recorded by observing the interface between liquids due to the difference in refractive indices. The flow in the channel was created using "KDS Gemini 88" double syringe pump, which allowed setting the flow rate with a relative error of 0.35 %. The schematic diagram of the experimental setup is shown in Figure. 1.

Physical properties of the liquids used in the experiment were measured. These data are given in Table 1. The viscosity of the oils was measured using a rotary viscometer, at that the relative measurement error was 3 %. The density was measured by weighing a known volume of liquid, with a relative error of 1 %. Measurement of wetting contact angles and surface tension was carried out using KRUSS DSA-100 (Germany) device. Surface and interfacial tension were measured by the pendant drop method. The measurement uncertainty did not exceed 2 %. Contact angles were measured by a direct goniometric method using different models to approximate the shape of the droplet surface.

For plug length measurements special software developed in the Kutateladze Institute of Thermophysics was used in order to process flow images obtained during flow visualization. Uncertainty of plug length measurements was about 2 pixels, which corresponds to 4 μm. The averaging over a number of plugs was done for every value of flow rates.

3. Mathematical model

In this research, to simulate two-phase flow in a T-type microchannel we used a numerical technique based on the Volume of Fluid (VOF) method, which is well established for the calculation of macroscopic flows with a free surface [30, 31]. The idea of the VOF method

consists in the fact that fluids are considered as a single two-component medium, and the spatial distribution of the phases within the estimated region is determined by means of a special marker function F(x,y,z,t), whose value specifies the volume fraction of the liquid phase in the computational cell in a following way: F(x,y,z,t)=0 if the cell is empty, and F(x,y,z,t)=1 if the cell is completely filled with liquid.

Since the free surface moves together with the liquid, tracking the movement of the free interface in space is carried out by solving the equation of the volume fraction transfer of the liquid phase in the cell:

$$\frac{\partial F}{\partial t} + \mathbf{V} \cdot \nabla F = 0 \tag{1}$$

the velocity vector of a two-phase medium found from the solution of a system of hydrodynamic equations consisting of a mass conservation equation or a continuity equation

$$\frac{d\rho}{dt} + \nabla(\rho \cdot \mathbf{V}) = 0 \tag{2}$$

and motion or momentum conservation equations:

$$\frac{d\rho\mathbf{V}}{dt} + \nabla(\rho\mathbf{V} \times \mathbf{V}) = -\nabla p + \nabla(\boldsymbol{\tau}) + \mathbf{F} \tag{3}$$

The components of the viscous stress tensor are defined as:

$$\boldsymbol{\tau}_{ij} = \mu \left(\frac{dU_i}{dx_j} + \frac{dU_j}{dx_i} - \frac{2}{3}\delta_{ij}\frac{dU_k}{dx_k} \right) \tag{4}$$

The density and molecular viscosity of the considered two-component fluid are found through the volume ratio of the liquid in the cell according to the mixture rule:

$$\rho = \rho_1 F + (1-F)\rho_2 \tag{5}$$

$$\mu = \mu_1 F + (1-F)\mu_2 \tag{6}$$

When considering fluid flow with the interface, one has to deal with the surface tension phenomenon which cannot be neglected in the case of microchannel flow. The study of flow driven by surface tension is generally a challenging task. Therefore, the advantage of the VOF method consists in the fact that this method allows relatively simply taking into account the influence of surface tension forces. The most common way to simulate surface tension in the framework of the VOF method is to use the CSF (Continuum Surface Force) algorithm [30], whose essence consists in the introduction into the motion equations of an additional volumetric force, whose value is determined from the correlation:

$$\mathbf{F}_s = \sigma k \nabla F \tag{7}$$

4

curvature of the free surface, which is defined as the divergence of the normal vector:

$$k = \nabla\left(\frac{\mathbf{n}}{|\mathbf{n}|}\right) \tag{8}$$

The normal to the free surface is calculated as the gradient of the volume ratio of the liquid phase in the cell:

$$\mathbf{n} = \nabla F \tag{9}$$

At that, the value of the normal vector on a solid wall is determined by the wetting contact angle:

$$\mathbf{n} = \mathbf{n_W}\cos\theta + \boldsymbol{\tau_W}\sin\theta \tag{10}$$

similarly, as in the work [24], where in particular the influence of wetting contact angle on the slug formation is considered.

The method used is described in detail in the paper [32]. Here we note the main points of the numerical simulation. The difference analogue of the convective-diffusion equations is found using the finite volume method for structured multi-block grids, which automatically ensures the conservatism of the resulting scheme. The connection between the velocity and pressure fields is realized through SIMPLEC procedure on the combined grids.

To approximate convective terms of the hydrodynamics equations we used QUICK counter flow scheme of the second order. The solution of hydrodynamic equations was carried out in an implicit formulation. To approximate the non-stationary terms of the hydrodynamics equations, an implicit scheme of the second order was used. Approximation of the convective transport equation of the volume ratio of the liquid in the cells was carried out by means of an explicit TVD Compressive scheme, providing high resolution of the phase interface. Diffusion flux and source terms were approximated by second order of accuracy. The Green-Gauss node based gradient calculation schemes were used for the momentum-continuity equations and the pressure gradient calculations.

The staggered grids with PRESTO discretization scheme for pressure where used. PRESTO discretization gives more accurate results since interpolation errors and pressure gradient assumptions on boundaries are avoided. This scheme works better for problems with strong body forces (surface tension) and high density ratio. PRESTO however, is more computationally costly, since you need more memory.

Preliminary calculations showed that good agreement with the experiment can be obtained using a computational grid with a total number of cells about 800000. Fragments of the calculated grid are shown in Figure 2. The numerous methodical calculations made it possible to

formulate some requirements for the computational grid particularization, the magnitude of the time step, and the numerical algorithms used. It was found that for correct simulation of two-liquid slug flow in microchannels it is necessary to have at least 5 grid points per film thickness between the channel wall and the slug (see Figure 2b). In this case, the optimal was the non-uniform grid with a maximum cell size of 36 μm and a minimum cell size of 0.7 μm. Further refinement of the grid as shown by the calculations does not lead to a change in the results.

The time step is controlled by a specified maximum value for the CFL (Courant–Friedrichs–Lewy), CFL = τV/h, where τ, h and V are the time step, grid size and fluid velocity respectively. A very high CFL value leads to an unstable numerical approach while a low CFL value means very small time steps and consequently long simulation times. A maximum CFL of 2 was adopted in this work. A typical value of the time step depending on the flow regime was from 10^{-3} to 10^{-6}s.

The convergence criteria for velocities and pressure were set to 0.0005. The absolute values of residuals achieved were found to be sufficiently low, $O(10^{-6})$ for velocities and $O(10^{-8})$ for pressure equations.

4. Results and discussion

In this study, the flow of immiscible liquids in a T-shaped microchannel was considered at different flow rates of castor and paraffin oils. The experimental investigation was carried out within a fairly wide range of flow rates that also provided a wide range of Reynolds number $Re = \dfrac{\rho \cdot U \cdot d}{\mu}$, $2.1 \cdot 10^{-5} < Re_p < 0.1$, $4 \cdot 10^{-6} < Re_c < 0.01$; and $We = \dfrac{\rho \cdot U^2 \cdot d}{\sigma}$, $1.7 \cdot 10^{-9} < We_p < 0.01$, $2 \cdot 10^{-9} < We_c < 0.01$; the capillary number $Ca = \dfrac{\mu \cdot U}{\sigma}$, $8 \cdot 10^{-5} < Ca_p < 0.1$, $4.8 \cdot 10^{-4} < Ca_c < 1.16$.

In consequence of flow visualization, the following flow regimes were established: parallel, rivulet, plug, slug, and droplet regimes. In the work [9] dimensionless parameter Weber number multiplied by Ohnesorge number (WeOh) was proposed for liquid-liquid flow pattern map construction. This parameter provides generalization of data for different sets of immiscible liquids in certain channel geometry. Therefore, here we use WeOh to plot a flow pattern map of our system, which is shown in Figure 3.

Numerical simulation was carried out for each of these regimes. The calculated domain corresponded to the experimental range with the following dimensions: inlet channels – 2400×200×200 μm, mixing channel – 6000×400×200 μm. Physical properties of liquids were determined through the experiment (Table 1). A structured calculation grid consisting of 800

thousand nodes was used for calculations. As the boundary conditions, the mass flow rates with a steady-state velocity profile were set at the inlets, while Neumann condition was set at the outlet of the microchannel. No-slip condition was set at the walls of the channel.

One of the tasks of the present work was to show that the chosen numerical method allows correctly simulating the object under study. The criterion for this can be the compliance of the numerical simulation results with the experimental data in terms of accurate reproduction of the flow regimes and the region of their existence, as well as the shape of the phase interface, and the length of the slugs. To debug the chosen numerical model, we considered several different combinations of the flow rates of both liquids for each flow regime registered in the experiment, and performed a numerical simulation.

The numerous methodical calculations made it possible to formulate some requirements for the computational grid particularization, the magnitude of the time step, and the numerical algorithms used. It was found that for correct simulation of two-liquid slug flow in microchannels it is necessary to have at least 5 grid points per film thickness between the channel wall and the slug. The magnitude of the time step should be determined based on the conditions CFL<2 (Courant–Friedrichs–Lewy). To approximate convective terms of the hydrodynamics equations we used QUICK counter flow scheme of the second order. The solution of hydrodynamic equations was carried out in an implicit formulation. To approximate the non-stationary terms of the hydrodynamics equations, an implicit scheme of the first order was used. Approximation of the convective transport equation of the volume ratio of the liquid in the cells was carried out by means of an explicit TVD Compressive scheme, providing high resolution of the phase interface. Diffusion flux and source terms were approximated by second order of accuracy.

The wetting contact angle, defined as the angle between the solid surface and the tangent at the point of the three phases contact, is the measure of surface wettability. In the case of two-phase flow in a microchannel, the dynamic contact angle, whose modeling is quite a challenging task, plays an important role. It is almost impossible to choose a universal correlation for the dynamic contact angle. In addition to the main parameters, there are also other characteristics, such as surface roughness and heterogeneity, which affect the dynamic contact angle.

In this paper, the model proposed in [33] was chosen to determine the dynamic contact angle. This model is based on the use of the equilibrium value of the contact angle and the capillary number:

$$\theta_d = f(Ca + f^{-1}(\theta)) ,$$

$$f = \arccos\left\{1 - 2\tanh\left(5.16\left(\frac{x}{1+1.31x^{0.99}}\right)^{0.706}\right)\right\},$$

$$x = Ca + f^{-1}(\theta), \, Ca = \frac{\mu U_{CL}}{\sigma}.$$

Here the velocity of the contact line was defined as the scalar product of the normal vector of the phase interface on the flow velocity vector in the cell closest to the wall.

In addition to the Kistler model [33], a simpler model was considered to determine the dynamic contact angle, in which the value of the contact angle is selected based on the motion direction of the contact line:

$$\theta_d(U_{CL}) = \begin{cases} \theta_{mda} & \text{if } U_{CL} > 0 \\ \theta_{mdr} & \text{if } U_{CL} < 0 \end{cases}$$

When carrying out methodical calculations, it was revealed that the model with switching the contact angle depending on the sign of the contact line velocity, despite the simplicity of implementation, has a number of serious computational difficulties associated with the stability of the numerical algorithm. Abrupt switching from one contact angle to another leads to oscillations of the whole iteration process that may result in non-physical oscillations of the contact line. Therefore, it was decided to use the Kistler model.

Figure 4 presents the calculation results and experimental data for two cases corresponding to the parallel regime. Here paraffin oil is supplied from above while castor oil is supplied from below. As is obvious, in this regime, the liquids in the mixing channel move in layers parallel to each other. At such flow velocities, the inertia forces significantly exceed the interfacial tension forces, and the interface between the fluids is almost flat. A qualitative comparison of the calculation results with experimental photographs for the parallel flow regime shows that the calculation generally reproduces the experiment in terms of the interface shape and the thickness of the liquid layers in different regimes.

Analysis of the obtained velocity fields shows that even in the case of equal volumetric flow rates, the liquids move at significantly different velocities due to the fact that the thickness of the layers in the mixing channel is different. Thus, in the first case (Qp=12 µl/min, Qc=12 µl/min) the flow rate in the paraffin oil layer is about 2.5 times higher than that in castor oil.

With a decrease in the flow rate of paraffin oil, a so-called rivulet regime is formed. In this regime, paraffin oil flows along the side wall of the mixing channel in the form of a rivulet. A typical pattern of such a flow is shown in Figure 5 for the case of Qp=6 µl/min, Qc=48 µl/min. At that, it should be noted that for the rivulet regime in both the calculations and experiments, a

quasi-stationary behavior was observed in which most of the time the rivulet was stationary, but at some points in time it changed its position and adhered to one or the other wall of the channel. Figure 5 shows an example of such behavior.

A qualitative comparison of the calculation and experiment for the rivulet flow regime is shown in Figure 6. Here, as in most of the observed rivulet flow regimes, a rivulet of paraffin oil at the inlet propagates along the near-side wall of the outlet channel, thus resembling a parallel flow regime. However, in contrast to the parallel flow regime, the rivulet of paraffin oil changes its position downstream and can propagate along any wall of the outlet channel not necessarily occupying its entire width.

With a significant reduction in the flow rate of both liquids, the interfacial tension forces begin to dominate over the inertia forces, and paraffin oil slugs are formed in the mixing channel. Figure 7 shows a qualitative comparison of the calculation results with experimental photographs at the stage of slug formation for one of the considered cases of the slug flow regime (Q_c=0.05 µl/min, Q_p=0.05 µl/min). The figures show the flow pattern corresponding to four consecutive points in time presenting formation dynamics and movement of paraffin oil slugs in the castor oil. As is obvious, there is a good qualitative agreement of experimental photographs and results of numerical simulation, not only at the stage of movement of individual slugs, but, most importantly, at the stage of their formation. The shapes of phase interface in the calculation and experiment at similar time points agree very well that indicates a good resolution of the computational algorithm.

The flow pattern for the slug regime at other fluid flow rate ratios is shown in Figure 8. Analysis of the simulation results and experiments has shown that at a fixed flow rate of paraffin oil and an increase in the flow rate of castor oil, the distance between the slugs increases. At that, the length of the slugs decreases. With an increase in the flow rate of paraffin oil at a fixed flow rate of castor oil, the length of the paraffin oil slugs increases. Accordingly, the distance between the slugs is reduced. The length of the slug is the most important quantitative characteristic of this flow regime. This parameter is important from a practical standpoint, because it affects the characteristics of heat and mass transfer processes in such a mixture.

The dependence of the slug length, non-dimensionalized by the hydraulic diameter of the channel, on the ratio of the flow rates of castor and paraffin oils is shown in Figure 9. Analysis of the data obtained has shown that the dimensionless length of the slugs is well described by the following correlation: $L/d = 1+1.45(Q_p/Q_c)$, which corresponds to the correlation suggested by [15]. Figure 9 presents also the comparison of calculation and experimental data on slug length. In general, the discrepancy between the calculation and the experiment does not exceed 5%. For

comparison, the Figure 9 also shows experimental data from the paper [15], and the results of numerical simulation from the work [27]. In these papers, the flow of water slugs in the oil was investigated in microchannels with a cross-sectional size 100x33µm. As can be seen, our experimental and calculated results are in good agreement with the data of other authors.

An increase in the flow rate of castor oil at a fixed flow rate of paraffin oil, results in formation of a droplet flow regime. In this regime, the flow of castor oil detaches individual droplets from the outlet jet of paraffin oil. This regime is shown in Figure 10 for the two flow rate ratios. At that, the distance between the droplets becomes very significant. Thus, for the case of Qp=0.05 µl/min and Qc=1.5 µl/min the distance between the droplets of paraffin oil is about 8000 µm. With increase in castor oil flow rate, the droplet size decreases while the distance between the droplets increases. Comparison of calculation and experimental data for droplet regime has shown that in general the calculations well reproduce both the size of the droplets formed, and the distance between them.

At high flow rates of paraffin oil, sliding slug flow regime is formed. In this regime, the mixing channel is almost completely filled with paraffin oil, while a layer of castor oil flows along the side wall of the channel. The visualization of this regime is shown in Figure 11. In this case, the castor oil flow is wave. At the beginning, a layer of castor oil accumulates for a long time. This layer thickens and moves farther from the inlet down the stream. After castor oil layer reaches a certain thickness, it ruptures and is demolished down to the flow. After that, the process is repeated again.

5. Conclusion

For a set of highly viscous immiscible liquids (paraffin and castor oil), the flow regimes were visualized within a wide range of flow rates of both phases. Parallel, rivulet, plug, slug, and droplet flow regimes were revealed, as well as the areas of their existence were defined. For the slug flow regime, the length and velocity of slugs were measured. The method of direct numerical simulation with VOF technique of phase resolution was used for numerical simulation. The Kistler model was employed to simulate the wetting contact angle. The results of numerical simulation confirmed the existence of the flow regimes observed in the experiment. The calculated and experimental data were compared. It is shown that all regimes recorded in the experiment are reproduced in numerical simulation at the corresponding phases flow rates. The shape of the phase interface is also well reproduced in numerical simulations.

Acknowledgments

List of Symbols

F	volumetric forces vector, N		Ca	Capillary number
F$_S$	additional volumetric force, N			
f	the Hoffman function		**Greek Symbols**	
n	normal vector		k	curvature of the free surface
$\boldsymbol{n}_w$	normal components of the vector with respect to the wall		μ	dynamic viscosity of a two-phase medium, Pa·s
p	static pressure, N/m²		$\boldsymbol{\tau}$	viscous stress tensor,
Qc	flow rate castor oil, m³/s		σ	surface tension coefficient, N/m
Qp	flow rate paraffin oil, m³/s		θ	contact angle, deg.
Re	Reynolds number		θ_d	dynamic contact angle, deg.
U_{ij}	the components of the velocity vector, m/s		$\boldsymbol{\tau}_w$	tangential components of the vector with respect to the wall
U_{CL}	velocity of the contact line, m/s		θ_{mda}	maximum dynamic advancing angle, deg.
V	velocity vector of a two-phase medium, m/s		θ_{mdr}	minimum dynamic receding angle, deg.
We	Weber number		ρ	density of the two-phase medium, kg/m³

References

1. Novak, U., Pohar, A., Plazl, I., & Žnidaršič-Plazl, P (2012) Ionic liquid-based aqueous two-phase extraction within a microchannel system. Separation and Purification Technology 97: 172–178.
2. Tsaoulidis, D., & Angeli, P (2015) Effect of channel size on mass transfer during liquid – liquid plug flow in small scale extractors. Chemical engineering journal 262: 785–793.
3. Ducry, L., & Roberge, D. M (2005) Controlled autocatalytic nitration of phenol in a microreactor. Angewandte Chemie - International Edition 44(48): 7972–7975.
4. Li, Y., Yamane, D. G., Li, S., Biswas, S., Reddy, R. K., Goettert, J. S., Kumar, C. S. S. R. (2013) Geometric optimization of liquid-liquid slug flow in a flow-focusing millifluidic device for synthesis of nanomaterials. Chemical Engineering Journal 217: 447–459.
5. Šalić, A., Tušek, A., & Zelić, B (2012) Application of microreactors in medicine and biomedicine. Journal of Applied Biomedicine 10(3): 137–153.
6. Tran, T. M., Lan, F., Thompson, C. S., & Abate, a R (2013) From tubes to drops: droplet-based microfluidics for ultrahigh-throughput biology. Journal of Physics D: Applied Physics 46(11): 114004.
7. Roberge, D. M., Ducry, L., Bieler, N., Cretton, P., & Zimmermann, B (2005) Microreactor technology: A revolution for the fine chemical and pharmaceutical industries, Chemical Engineering and Technology 28(3): 318–323.
8. Foroughi, H., & Kawaji, M. (2011) Viscous oil-water flows in a microchannel initially saturated with oil: Flow patterns and pressure drop characteristics. International Journal of Multiphase Flow 37(9): 1147–1155.

9. Yagodnitsyna, A. A., Kovalev, A. V, & Bilsky, A. V. (2016) Flow patterns of immiscible liquid-liquid flow in a rectangular microchannel with T-junction. Chemical Engineering Journal 303: 547–554.

10. Yagodnitsyna, A. A., Kovalev, A. V, & Bilsky, A. V. (2017) Experimental study of ionic liquid-water flow in T- shaped microchannels with different aspect ratios. Journal of Physics: Conf. Series 899: 32026.

11. Zhao, Y., Chen, G., & Yuan, Q. (2006) Liquid-Liquid Two-Phase Flow Patterns in a Rectangular Microchannel. AIChE Journal 52(12): 4052–4060.

12. Wu, Z., Cao, Z., & Sundén, B. (2017) Liquid-liquid flow patterns and slug hydrodynamics in square microchannels of cross-shaped junctions. Chemical Engineering Science 174: 56–66.

13. Kashid, M., & Kiwi-Minsker, L. (2011) Quantitative prediction of flow patterns in liquid-liquid flow in micro-capillaries. Chemical Engineering and Processing: Process Intensification 50(10): 972–978.

14. Waelchli, S., & Rudolf von Rohr, P. (2006) Two-phase flow characteristics in gas-liquid microreactors. International Journal of Multiphase Flow 32(7): 791–806.

15. Garstecki, P., Fuerstman, M. J., Stone, H. a, & Whitesides, G. M. (2006) Formation of droplets and bubbles in a microfluidic T-junction-scaling and mechanism of break-up. Lab on a Chip 6(3): 437–446.

16. Xu, J. H., Li, S. W., Tan, J., & Luo, G. S. (2008). Correlations of droplet formation in T-junction microfluidic devices: From squeezing to dripping. Microfluidics and Nanofluidics 5(6): 711–717.

17. Su, Y., Chen, G., Yuan, Q. (2014) Effect of Viscosity on the Hydrodynamics of Liquid Processes in Microchannels. Chemical Engineering Technology 37 (3): 427-434.

18. Claire, M., Jean-François, B., & Laurent, P. (2018). Effects of Process Parameters on an Inverse Concentrated Miniemulsion Flowing in a Microchannel. Chemical Engineering & Technology 41(10): 1965-1974.

19. Minqiang, P., Yi, Z., Kambiz, V. (2017) Velocity Uniformity of Microchannels in a Laminated-Sheet Structure Under Parallel and Series Methods. Chemical Engineering & Technology 40(10): 1774-1783.

20. Nauman, K., Isao, K., &Kunihiko, U. (2017) Asymmetrical Microchannel Emulsification Plates for Production of Small - Sized Monodispersed Emulsion Droplets. Chemical Engineering & Technology 40(12): 2351 – 2355.

21. Salim, A., Fourar, M., & Sausse, J. (2008) Oil-water two-phase flow in microchannels: FLow patterns and pressure drop measurements. Canadian Journal of Chemical Engineering 86(6): 978–988.

22. Li, Q., & Angeli, P. (2017) Experimental and numerical hydrodynamic studies of ionic liquid-aqueous plug flow in small channels. Chemical Engineering Journal 328: 717–736.

23. Gupta, R., Leung, S. S. Y., Manica, R., Fletcher, D. F., & Haynes, B. S. (2013) Hydrodynamics of liquid-liquid Taylor flow in microchannels. Chemical Engineering Science 92: 180–189.

24. Li, Y., Reddy, R. K., Kumar, C. S. S. R., & Nandakumar, K. (2014) Computational investigations of the mixing performance inside liquid slugs generated by a microfluidic T-junction. Biomicrofluidics 8(5): 1–18.

25. Sarrazin, F., Bonometti, T., Prat, L., Gourdon, C., & Magnaudet, J. (2008) Hydrodynamic structures of droplets engineered in rectangular micro-channels. Microfluidics and Nanofluidics 5(1): 131–137.

26. Kashid, M. N., Platte, F., Agar, D. W., & Turek, S. (2007) Computational modelling of slug flow in a capillary microreactor. Journal of Computational and Applied Mathematics 203(2 SPEC. ISS.), 487–497.

27. Raj, R., Mathur, N., & Buwa, V. V. (2010) Numerical Simulations of Liquid - Liquid Flows in Microchannels. Ind. Eng. Chem. Res. 49: 10606–10614.

28. Talimi, V., Muzychka, Y. S., & Kocabiyik, S. (2012) A review on numerical studies of slug flow hydrodynamics and heat transfer in microtubes and microchannels. International Journal of Multiphase Flow 39: 88–104.

29. Wörner, M. (2012) Numerical modeling of multiphase flows in microfluidics and micro process engineering: A review of methods and applications. Microfluidics and Nanofluidics 12(6): 841–886.

30. Brackbill, J. U., Kothe, D. B., & Zemach, C. (1992) A continuum method for modeling surface tension. J. Comput. Phys., 100, 335–354.

31. Hirt C.W., N. B. D. (1981) Volume of fluid (VOF) methods for the dynamic of free boundaries. J. Comput. Phys. 39: 201–226.

32. Minakov, A. V. (2014) Numerical algorithm for moving-boundary fluid dynamics problems and its testing. Computational Mathematics and Mathematical Physics, 54(10): 1560–1570.

33. Kistler, S.F. (1993) Hydrodynamics of wetting, in: J.C. Berg (Ed.), Wettability, Marcel Dekker Inc., New York.

1. **TABLE 1:** Physical properties of the liquids.

Physical properties	Paraffin oil	Castor oil
Density, kg/m^3	845	935
Viscosity, mPa*s	110	650
Wetting contact angle, deg	25	152
Interfacial tension, mN/m	17	

Figure 1: Schematic diagram of the experimental setup.

Figure 2: A fragment of the computational mesh in the central section of the channel (a), and the computational grid in the near-wall region (b).

Figure 3: Flow regime map of castor and paraffin oils mixture in a T-type microchannel.

Figure 4: Parallel flow regime. The experiment is on the left, the calculation is on the right.

a) Q_p=12 µl/min (Ca_p=0.032) and Q_c=12 µl/min (Ca_c=0.19); b) Q_p=240 µl/min (Ca_p=0.65) and Q_c=64 µl/min (Ca_c=1.02).

Figure 5: The distribution of the castor oil at the walls of the channel in the rivulet flow regime: Q_p=6 µl/min (Ca_p=0.017), Q_c=48 µl/min (Ca_c=0.76).

Figure 6: Rivulet flow regime for Q_p=6 µl/min (Ca_p=0.017), Q_c=48 µl/min (Ca_c=0.76). The experiment is on the left.

Figure 7: Comparison of calculation and experiment at the stage of paraffin oil slug formation in castor oil Q_p=0.05 µl/min (Ca_p=0.00014), Q_c=0.05 µl/min(Ca_c=0.0008).

Figure 8: Slug flow regime of paraffin oil in castor oil. Q_p=0.05 µl/min (Ca_p=0.00014) and Q_c=0.2 µl/min (Ca_c=0.003).

Figure 9: The dependence of the dimensionless slug length on the flow rates ratio. Here: crosses show experimental data, rhombuses are calculated data, solid curve corresponds to the proposed correlation, blue and red triangles are experimental data P. Garstecki et. al. [15] for viscosity 10 and 100 mPa×s, green dots - calculated data of R. Raj et. al. [27].

Figure 10: Droplet flow regime. a) Q_p=0.05 µl/min (Ca_p=0.00014), Q_c=0.8 µl/min (Ca_c=0.0123); b) Q_p=0.05 µl/min (Ca_p=0.00014), Q_c=1.5 µl/min (Ca_c=0.024).

Figure 11: Slug flow regime at Q_p=2 µl/min (Ca_p=0.005) and Q_c=0.1 µl/min (Ca_c=0.0016).