The study of monodisperse water-in-oil macroemulsion dynamics in a microfluidic chip

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Abstract. Emulsion dynamics is little-studied, but important subject for biological, medical and physical applications. In this work microfluidic droplet generator was used to experimentally study two-dimensional flow of monodispersed macroemulsion with 25 – 50 µm droplet size. Quantity of droplets, their trajectories and velocity profiles were studied. Obtained results showed, that velocity profile of droplets flow does not coincide with the Poiseuille profile of laminar oil flow in the channel. Droplet velocity decrease with the increasing of droplets concentration, which can be explained by the hydrodynamic interactions between droplets. The law of motion can be well described by the Greenberg’s traffic flow model.

1. Introduction
An emulsion is a mixture of two immiscible substances. It usually contains microdrops of one fluid, called dispersed phase, suspended in another fluid, called continuous phase. Nowadays, these systems are used in various fields such as food industry, car chemicals, beauty products etc.

Modern microfluidic technologies make it possible to produce monodisperse macroemulsions, which can be used as analytical framework for clinical diagnostics, pharmacological screening of drugs, biomarker analysis etc. Developing the theory of emulsion dynamics is important for understanding streams of blood and other body fluids. In addition, emulsions can be used for modeling some micro- and macroscopic interactions inside many-body systems. It is known from hydrodynamics that one moving liquid droplet creates 2D-dipole-like fluid flow field around it [1, 2]. Because of that, it is possible to use a system of droplets as an illustrative model of magnetic or electric dipole flows. Emulsions can also be used for self-assembling applications [3], which is another reason of researching their dynamics.

In this work, we studied dependence of droplet velocities from the emulsion concentration in 2D fluid flow inside a microfluidic channel.

2. Methods
The microfluidic chip with a flow-focusing droplet generator and elongated (10 mm) outlet channel (Figure 1a) was fabricated using soft lithography method from PDMS Sylgard 184 (Dow Corning) [4].

The droplet generator’s operating principle is based on the fact that the continuous phase flowing from two side channels meets the dispersed phase at the channel’s intersection, where the dispersed phase is squeezed by the continuous phase and breaks up into droplets (Figure 1b) [5]. Changing the flow rates of the liquids, it is possible to produce monodisperse macroemulsions with defined droplet size (Figure 1c).
In this work, we studied droplets 25 - 50 µm in diameter. Mineral light oil (cat. N. 330779 Sigma-Aldrich) with 3.5% ABIL EM 180 surfactant (Evonik Industries) was used as a continuous phase and deionized water as a dispersed phase. Chip’s sidewalls were hydrophobized with ClearVue Rain Repellent (Turtle Wax Inc.). For introducing continuous and dispersed phases into the microfluidic chip under the constant pressure in the range 8 – 30 kPa, we used a microfluidic pressure controller based on ITV001 electro-pneumatic regulators (SMC, Japan). The chip was mounted on an optical microscope Leica DM4000 B LED (Leica Microsystems) and after the generator stabilization, the droplets motion was recorded using a camera Pike F100B (Allied Vision Technologies) at 60 fps in the middle of the outlet channel.

![Chip with long outlet capillary; Flow-focusing generator; Droplets in the outlet channel at oil pressure 8 kPa, water pressure 6.5 kPa, droplet size 27 µm.](Figure 1)

Data was detected far from the droplet generator, so perturbations, created by it, did not influence on the flow. Matlab R2014a (MathWorks) was used for data processing, which included recognition of droplets, definition of their trajectories and individual droplets velocities calculation.

3. Results and discussion

It is well known that laminar fluid flows occur at low Reynolds numbers (in our case Re ~ 10^-4) and have a Poiseuille parabolic velocity profile with the maximum in the center of the channel [6]. Droplets in such a flow interact with each other hydrodynamically. Dipole forces in such systems are opposite to the direction of the flow. In a 1D droplet chain, this interaction causes reduction of droplet’s velocity, known as a collective drag reduction or peloton effect [1]. In a 2D droplet flow, there are possible options: droplets occupy the entire channel and droplets flow mostly in the center of the channel. In the first case, velocities of all droplets are close to each other and emulsion is moving as a uniform substance. In the second case despite the fact that the continuous phase has a Poiseuille velocity profile, the droplets velocity in the center of the channel is less than near the sidewalls (Figure 2a).

![Droplet flow and velocity profile at oil pressure 11 kPa, water pressure 8.7 kPa, droplet size 35 µm; Density and velocity profiles at above-mentioned pressures.](Figure 2)
After the analysis of about $10^4$ droplets’ trajectories, we have seen that near the center of the channel, where the droplet flow density is higher, droplet velocities are lower, than the velocities of drops, moving far from channel’s center (Figure 2b). In the areas with the highest droplets’ concentration, their velocity decreased thereby collective drag reduction – two dimensional peloton effect.

Theoretical analysis of droplet flows can be performed in terms of continuity models and models of automodel motion, which are based on the continuity equation. Due to low interaction between moving droplets in the orthogonal direction to the direction of motion friction forces can be neglected and the Euler equation can be used to describe the flow:

$$\frac{dv}{dt} = -\rho^{-1} \nabla p = -\rho^{-1} \frac{\partial p}{\partial \rho} \frac{\partial \rho}{\partial x}$$

Hence, equation of motion is:

$$\frac{dv}{dt} = -C^2 \rho^{-1} \frac{\partial p}{\partial \rho}$$

where $C = \frac{\partial p}{\partial \rho} > 0$ – sound velocity in the emulsion (cm/s).

From this equation, dependence of the velocity on the density (Figure 3) can be approximated by Greenberg’s model of traffic flow [7] with an addition, describing the floor value of velocity:

$$v = v_0 + Cln \frac{\rho_{max}}{\rho}$$

where $\rho_{max}$ is the density of close-packing system of droplets (cm$^{-1}$), $v_0$ - velocity of close-packing system of droplets (cm/s), at above-mentioned pressures $\rho_{max} = 137$ cm$^{-1}$, $v_0 = 0.016$ cm/s.

The difference between this model and Greenberg’s model is in the velocity of the close-packing system: on the road this case means, that the traffic flow velocity is zero, but in our case, the oil flow pushes it with the constant velocity.

![Dependence of the velocity on the density](image)

**Figure 3.** Example of dependence of droplet flow’s velocity on density at oil pressure 11 kPa, water pressure 8.7 kPa.
4. Conclusion
The velocity and density profiles of monodisperse water-in-oil macroemulsion flow were obtained. Investigated the mismatch between velocity profiles of laminar flow of classical fluid and macroemulsion, caused by collective hydrodynamic interactions. The dependence of the velocity on the droplet concentration was studied. Proved, that macroemulsion’s flow can be described in terms of motion of continuous compressible fluid. Based on the study of dependence of the velocity on the density of the droplet flow, it shown that such system motion could be approximated by modified Greenberg’s model of traffic flow. That means, macroemulsion flows can be used for demonstrable simulation of the traffic on the road. In addition, at oil pressure 11 kPa and water pressure 8.7 kPa, the sound velocity in emulsion with respect to Greenberg’s model is 0.01 cm/s, which correlates with results, obtained in [1].

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References
[1] Beatus T, Tlusty T, Bar-Ziv R 2006 Nature Physics 2 743-748
[2] Tlusty T 2006 Macromolecules 39 3927-3930
[3] Meissner M, Dong J, Eggers J, Seddon A M, Royall C P 2017 Soft Matter 13 788-794
[4] Bukatin A S, Mukhin I S, Malyshev E I, Kukhtevich I V, Evstrapov A A, Dubina M V 2016 Technical Physics Vol 61 No 10 pp 1566-1571
[5] Kukhtevich I V, Posmitnaya Y S, Belousov K I, Bukatin A S, Evstrapov A A 2015 NAUCHNOE PRIBOROSTROENIE Vol 25 No 3 pp 65–85
[6] Bruus H 2006 Theoretical microfluidics (MIC Lecture notes third edition) pp 28-30
[7] Greenberg H 1959 Operations Research Vol 7 pp 79–85