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Profiling oil-water flows in microchannel: preliminary results using Optical Feedback Interferometry

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Abstract

We study oil-water flows in a Y-shaped rectangular cross-section microreactor with different parameters at each inlet. A theoretical model based on a Couette flow approximation is proposed and Navier-Stokes equation is solved for the relative movement in between oil and water plates. The model is further validated with preliminary measurements for flow profile reconstruction using optical feedback interferometry. The proposed method shows potential applications in assessment of immiscible flowing fluids

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Introduction

Microfluidics continues to be an active area in research, covering a wide range of applications in chemical, biological and medical engineering. The characterization of fluid flows in microchannels has been particularly interesting for the scientific community, whereas the measurement of physical parameters related to motion is still of great interest for the interrogation of fluids at the micro-scale in diverse scenarios. In this context, there exist some interferometric techniques such as laser Doppler velocimetry [1] and biospeckle particle image velocimetry (PIV) [2] and methods for measuring velocity using temporal correlation of images such as dual-slit [3]. These methods show potential possibilities for their implementation in lab-on-chip systems and optofluidic devices, where the measurement of local velocity is necessary to accurately control flow at the micro scale and its consequent impact on quality control of industrial processes.

Optical feedback interferometry (OFI) in semiconductor laser has been recently explored for the characterization of velocity distribution in microchannels [4], with successful reconstruction of the profile of Newtonian and shear-thinning fluids. Later on, a direct implementation of an optical feedback flow sensor was proposed [5], thus reducing considerably the sensor size and costs. This technique is attractive in the sense of the minimal optical component needed for specific sensing applications because the laser is used as emitter as well as receiver, thus reducing considerably OFI sensors size when it is needed to measure physical parameters such as velocity and flow rate.

Several reports of OFI sensors for flows assessment were presented for those cases when the channel contained only one fluid [6-7]. However, extending their possible implementation in fluidic systems carrying two or more fluids is still to be demonstrated. Moreover, most sensors using Doppler effect for sensing are employed for measuring two phase flows of non-stratified fluids, thus the dynamics are driven by bubbles or fingers of one phase in the other and very few has been reported regarding immiscible flowing fluids in the absence of bubbles and with a clear interface defining the volume occupied by each stratified flow.

In this paper, we present a next step in the application of the so-called self-mixing effect in semiconductor laser to reconstruct the profile of oil and water in a Y-shaped chemical microreactor, where the viscosity of each fluid defines the system hydrodynamics. We propose a theoretical model based on Couette flows to be compared to our experimentally measured velocity profile.

Physical model

Couette flows

Couette flows are defined as moving fluids confined in two plates and flowing under a gradient of pressure. In this particular approach, one plate is at rest and the other is the moving interface. In this case, Navier-Stokes equation is given by:

$$\nabla v = \frac{\Delta P}{\eta} \quad (1)$$

where v is the velocity of the fluid, ΔP is the gradient of pressure and η is the viscosity.

In a chemical microreactor with two immiscible flowing fluids, there is an influence of the viscosity dominating the hydrodynamics. If those fluids occupy the inner volume a well-developed interface will appear along the length of the microchannel and the fluids are stratified. This means that the operator affecting velocity has to be considered in the x-direction only and that the gradient of pressure is constant.

Let's consider the schema shown in Figure 1 representing a microchannel of width W containing oil and water in steady state and an interface parallel to the length (direction y). Let us solve Equation (1) for every fluid, denoting liquid 1 as the water and 2 as the oil. Boundary conditions need to be considered. Both flows in the microchannel comply with the no-slip condition and therefore, their velocity on the walls is null. Considering the water-wall as $-l_1$ and the oil-wall as $l_2 = W - l_1$ the boundary conditions would be: $v_1(-l_1) = v_2(l_2) = \sigma v$, where v_1 and v_2 are the velocity of water and oil respectively, v is the velocity in the interface and $0 \leq \sigma \ll 1$ is a parameter defining very slow velocities in the water-wall and oil-wall respectively. As shown in Figure 1, position $x(0)$ indicates the localization of the interface.

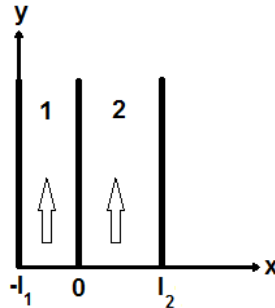


Figure 1: Graphical representation of oil and water in a microchannel. Arrows represent flow direction

Considering the elements above detailed, the velocity distribution in the microchannel is given by:

For water:

$$\frac{\partial^2 v_1}{\partial x^2} = \frac{\Delta P_1}{\eta_1} = A_1 \rightarrow v_1(x) = \frac{A_1 x^2}{2} + B_1 x + C_1 \quad (2)$$

For oil:

$$\frac{\partial^2 v_2}{\partial x^2} = \frac{\Delta P_2}{\eta_2} = A_2 \rightarrow v_2(x) = \frac{A_2 x^2}{2} + B_2 x + C_2 \quad (3)$$

Using their corresponding boundary conditions, the velocity distribution in the microchannel can be expressed as:

$$v_1(x) = \frac{A_1 x^2}{2} + \left[\frac{v}{l_1} (1 - \sigma_1) + \frac{A_1}{2} l_1 \right] x + v \quad \text{for } -l_1 < x < 0 \quad (4)$$

$$v_2(x) = \frac{A_2 x^2}{2} + \left[\frac{v}{l_2} (\sigma_2 - 1) - \frac{A_2}{2} l_2 \right] x + v \quad \text{for } 0 < x < l_2 \quad (5)$$

where σ_1 and σ_2 have the meaning of σ for water and oil respectively.

Optical feedback for fluid flow measurements

Optical feedback interferometry (OFI) is an alternative sensing technique useful for local measurement of flow velocity in microchannels. Moreover, its sensing scheme is simpler and costless compared to other techniques, guaranteeing flow profile reconstruction at the microscale with fairly good agreement with, for example, dual slit sensing method [8].

Depending on the laser, the power variations in the lasing cavity can be measured by monitoring the signal of the photodiode in the module, if included, or by using the changes in junction voltage when the laser is submitted to external feedback. The relation of power variations are then given by the formula:

$$P_t = P_0 \left\{ 1 + \cos \left[2\pi \frac{2(L + v_t t)}{c} \right] \right\} \quad (6)$$

where where P_0 is the optical power of the laser without feedback, L is the distance between the target and the laser, c is the speed of light, t is time and v_t is the projection of the target velocity onto the laser beam propagation axis.

OFI needs a small quantity of scatterers merged into the fluids. As long as this condition is satisfied, the interaction of the laser with these particles produces back-reflected light that enters in the laser cavity and changes its spectral properties. As in laser Doppler velocimetry, the power spectral density of the laser shows a fundamental Doppler frequency shift f_D that is related to the target velocity as follows:

$$f_D = \frac{2nv_t \cos(\theta)}{\lambda} \quad (7)$$

where n is the refractive index of the surrounding medium, v_r is the velocity of the particles embedded in the fluid, λ is the laser wavelength and θ is the angle between the laser and the channel.

f_D can be easily extracted from the power spectral density distribution of the laser signal that is monitored by any of the methods mentioned above. A function fitting consisting on a Gaussian, a Lorentzian or a combination of both can be employed for determining the Doppler frequency proportional to the fluid velocity [9].

Materials and methods

Set-up

The microreactor is constructed in SU8 over glass using optical lithography. The Y-shaped two-inlet microchannel has a $300 \times 100 \mu\text{m}$ rectangular cross-section and is 18 mm long from inlets to outlet. The channel containing both fluids from the junction to the outlet is 11 mm long.

The optical set-up employed during experimental work is shown in Figure 2. It consist on a laser diode (Thorlabs L785P090) emitting at 785 nm and driven by an injection current of 60 mA. The coherent radiation is focused with a single lens (Thorlabs C240TME-B) and pointed with an angle of 80° with respect to the propagation of the flow in the channel. The piece supporting the laser and the lens is connected to a 3D-stage computer-driven device that allows scanning the microchannel to reconstruct the velocity profile along the width of 300 μm .

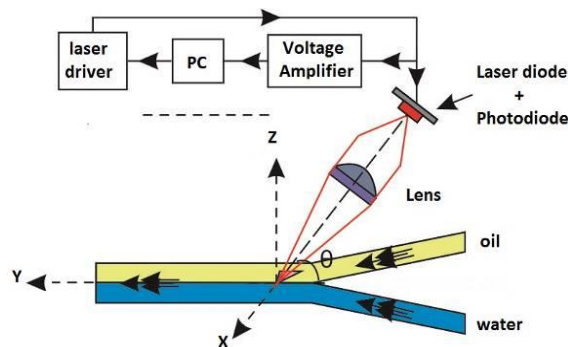


Figure 2: Experimental set-up

Fluids

Oil (Polydimethylsiloxane, Sigma Aldrich 481939) and demineralized water are used as the fluids in our study. Oil's viscosity and density were determined experimentally to be 28 mPa·s and 0.982 g/cm^3 respectively at 25°C . We merged a small concentration (0.4 % by mass) of 5 μm tracer polyamide particles (Dantec Dynamics 9080A3011) in the oil which density is 1.02 g/cm^3 and 1% of full-cream milk (determined by mass) is embedded in the water.

Experimental execution

First, a calibration step is carried out. Diluted milk concentrated at 2% by mass is pumped at constant flow rate by both inlets. The laser is positioned in the center of the channel and the Doppler frequency and signal to noise ratio is verified. Then, the stage device is employed to move the laser 150 μm until it reaches the water-wall. Using a single lens reduces the optical set-up and system costs. However, due to the beam collimation, the sensing volume might be large enough to detect a signal in the very low frequency range even if the laser spot is pointing the channel wall. We compensate this by considering σ in the no-slip condition in the model.

Both channels are cleaned with water and then oil and water are pumped inside the microreactor. Once the channel is filled and the flows have reached the steady state we performed several consecutive scans of the 11 mm-long-microchannel, 5 mm away from the junction. The 3D-stage micro-mechanical system is controlled by a LabVIEW[®] interface and measures 30 points along the width (x-direction) of the channel, from one wall to the other with steps of 10 μm .

Oil and demineralized water are pumped with a pressure-controlled pump (Fluigent MFCS-EZ-4C). The flow rate was fixed for oil at 1.5 $\mu\text{L}/\text{min}$ and was varied for water as follows: 20, 35 and 65 $\mu\text{L}/\text{min}$.

Signal acquisition and processing

We acquire temporal signals from the laser's photodiode at 500 KHz, which are later processed off-line in Matlab[®]. Then, we calculate the power spectral density of the autocorrelation of the signal. The spectrum is smoothed and a segment containing the desired Doppler peak is selected. Then, a function fitting is employed to obtain f_D and the velocity distribution. We extracted the Doppler frequency from an expression consisting of a Gaussian based function described by

$$\beta e^{\left(-\frac{(f-f_D)}{2\tau^2}\right)} - pf + q \quad (7)$$

where β is the height of the fundamental peak, f_D is the Doppler frequency, τ is the full width at half maximum, p is the slope of the linear term and q is the intercept with the SNR-axis in the spectrum.

Results

Figure 3a shows the volume occupied by each fluid in the microchannel. The water pushes the oil and as the flow rate is varied, it occupies a bigger portion of the inner volume.

The velocity distribution for both fluids is represented in Figure 3b. Both theoretical and experimental profiles are plotted as a function of position in the channel with the same resolution employed in the scan. Theoretical curves are represented using $\sigma_1 = \sigma_2 = 10^{-6}$.

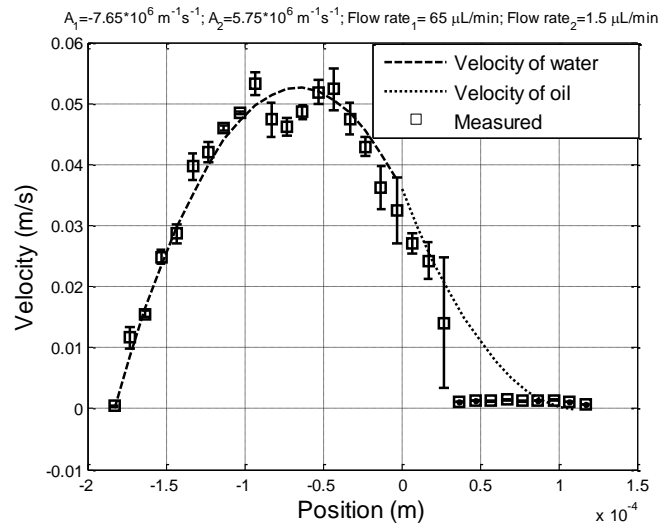
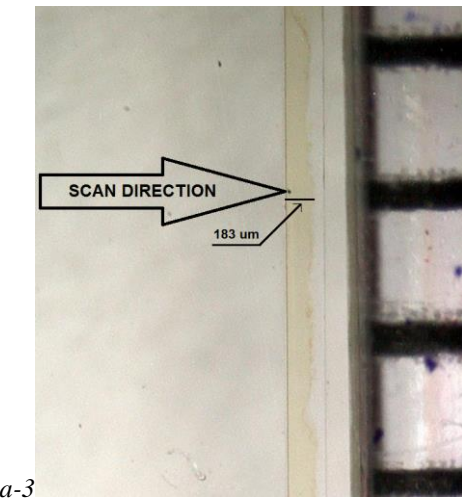
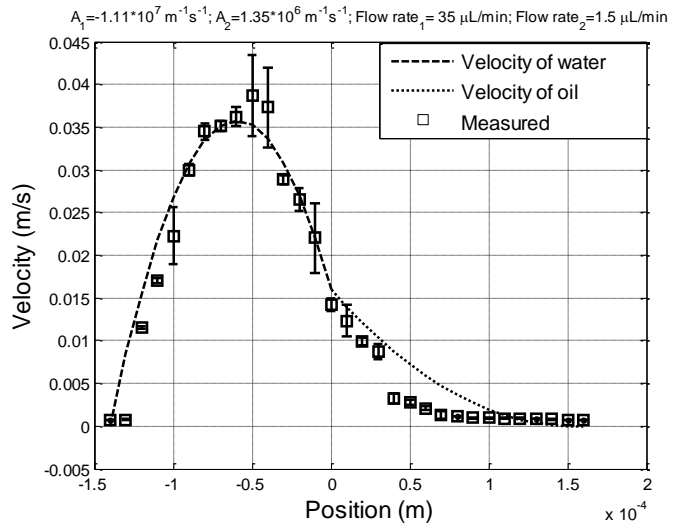
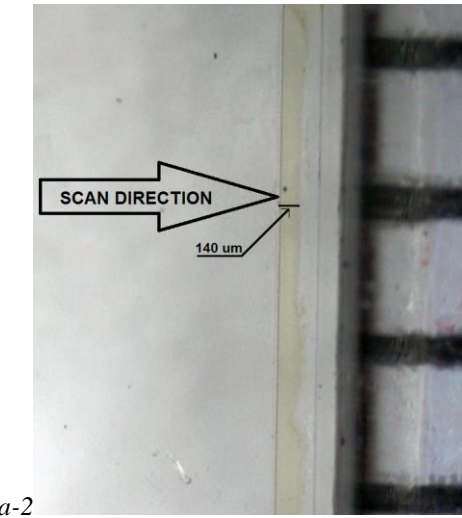
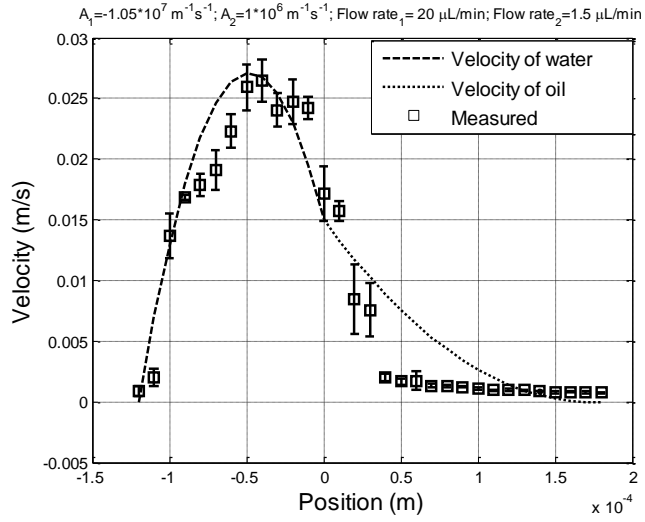
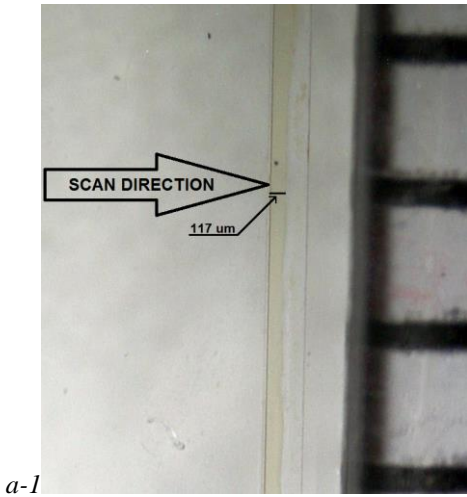


Figure 3: (a1-3) Volume occupied by each fluid at different flow rates. Betadine was added in water to enhance contrast between both fluids. (b1-3) Both measured (boxes with error bars for three measured profiles) and simulated (dashed and dotted lines) reconstructed profiles

As can be expected, due to its higher viscosity, oil shows a much lower velocity as compared to water. Thus a part of the profile on the oil side cannot be measured due to the lack of sensitivity of the sensor in the very low velocity range.

While the flow rate increases in the inlet, it induces an acceleration of the oil in the first layers at the vicinity of the interface thus allowing the sensor to perform valid measurements of the local flow speed.

Conclusions

We have proposed an optical feedback interferometer for profiling two immiscible flows in a Y-shaped microchannel. A theoretical model based on Couette flows was proposed and compared to our experimentally measured profiles and fairly good agreement was achieved. This set-up can be extended in the assessment of flowing fluids at the microscale and implemented in quality control routines in pharmaceutical, chemical and biomedical engineering

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