Alcohol jets investigations in a microchannel in a viscous outer medium

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Abstract. This paper is concerned with the experimental investigation of jets formation in a classic microchannel with low aspect ratio $a/r=0.125$. The confined jets are obtained in a Y-shaped microchannel using isopropyl alcohol and ethanol in a viscous outer medium represented by mineral oil. In the cases with high flow rate of the inner jets the interface has an important contribution on the velocity distribution inside the jet.

1. Introduction
The flowing regime and its prediction in microfluidic devices has an important role in multiple fields, such as ink jet printing, microbiology, chemistry and drug delivery [1,2]. Flow prediction and control was thoroughly investigated by Hu et al. [3] in a cross microchannel with a viscous outer medium and the same Rayleigh instability was investigated at macroscale by Pătraşcu et al. [4]. In this work we investigate in a microchannel the jetting regime that occurs in the case when on the central branch of the microchannel are introduced two types of alcohol, with similar density but different viscosity and interfacial tension with the outer medium.

2. Experimental details
The experimental setup used for jet formation is composed of a microchannel with trifurcation, inverted microscope, μPIV, camera and pressure pumps. The microchannel is created using soft lithography in polydimethylsiloxane (PDMS). Here, the microchannel was produced using three different PDMS layers, one layer for the sealing, one layer that has the microchannel shape and the final one which contains the microfluidic connectors. The three layers were aligned and bonded with RIE technology (reactive ion etching) using low power O\textsubscript{2} plasma.

The jets were obtained in the microchannel from figure 1 (a) by injecting mineral oil through the lateral branches and two different types of alcohol through the central branch of the microchannel as in figure 1 (c). The types of alcohol used here are ethanol (ETA) and isopropyl alcohol (IPA).
The interfacial tension was determined using the pendant drop method. This method is based on inspection of the characteristic shape of a pendant droplet. The underlying equation is derived from the Young-Laplace equation and turns out to be an inhomogeneous ODE and that is why it must be derived numerically. Drop shape is calculated for different values of the surface tension and is compared to the drop contour recorded from the image figure 1 (b). The closest matching geometry is determined and thus the surface tension is derived. The density of the fluid has to be determined prior to measuring the surface tension in order to find a single drop contour. The picture is taken just before the detachment when the droplet has a pear shape which means Bo≈1 (Bond number). With this method the surface and interfacial tension are measured in the static case.

The values of the material properties for the fluids used in this work are shown in Table 1.

| Fluid            | ρ [kg/m³] | η [Pa∙s] | σ [N/m] |
|------------------|-----------|----------|---------|
| Mineral Oil      | 873       | 0.16     | -       |
| Ethanol          | 789       | 0.0018   | 0.0046  |
| Isopropyl alcohol| 786       | 0.0024   | 0.0012  |

Five experimental cases are investigated for each type of alcohol using µPIV. For all the cases the input pressure of the mineral oil is kept constant at 200 mbar while for the alcohol the pressure varies from 150 to 340 mbar. The flow rate can be computed using the following analytical formula that takes into account the fact that the microchannel has a low aspect ratio [5]:

$$Q \approx \frac{h^3 w \Delta p}{12 \eta_0 L} \left(1 - 0.63 \frac{h}{w}\right),$$

where $h=50\mu m$ is the microchannel height, $w$ is the width, $\Delta p$ is the input pressure, $\eta_0$ is dynamic viscosity and $L=20 \text{ mm}$ the length of the microchannel. The average velocity before the entrance in the main channel is computed using Eq. 1 for each experimental case and the values displayed in Table 2 are in good agreement with the ones obtained using µPIV. The Brownian motion can be neglected, as in our cases the Brownian diffusion coefficient is by the order of $10^{-13}$ and the error is «1%.

| Fluid / Velocity [m/s]       | Case I 150 mbar | Case II 200 mbar | Case III 300 mbar | Case IV 320 mbar | Case V 340 mbar |
|------------------------------|-----------------|-----------------|------------------|-----------------|-----------------|
| Mineral Oil                  | 0.0005          |                 |                  |                 |                 |
| Ethanol                      | 0.091           | 0.121           | 0.181            | 0.194           | 0.206           |
| Isopropyl alcohol            | 0.045           | 0.059           | 0.089            | 0.095           | 0.101           |
3. Results and comments

The influence of the material properties can be directly seen in the difference between the values of the average velocity as the interface between the two liquid systems develops in a different way, as in figure 2. In all the cases, the alcohol jets are steady, and no external perturbations are induced. The flow rates of both liquids are low enough hence no instabilities occur. Even though from the flow visualizations the jets seem to have the same width, this is not true, and their corresponding widths are extracted from the µPIV measurements on a horizontal line, away from the main channel entrance, when the flow is fully developed, and the results are shown in Table 3.

Figure 2. Flow visualizations of jet formation on the five experimental cases with the pressure increasing in the central microchannel (I - 150, II - 200, III - 300, IV - 320 and V - 340 mbar) and the outer viscous liquid at a constant pressure (of 200 mbar)

Another difference between the two types of jets, besides the fully developed width is the interface width. In the case of isopropyl alcohol, the width is 18 µm and in the case of ethanol, we have a thinner interface, of 11 µm.

Table 3. Jet widths

| Liquid type/jet width [µm] | Case I | Case II | Case III | Case IV | Case V |
|---------------------------|--------|---------|----------|---------|-------|
| Isopropyl alcohol         | 140    | 221     | 286      | 305     | 335   |
| Ethanol                   | 123    | 178     | 252      | 267     | 281   |

In general, the velocity distribution inside the jet is parabolical as in figure 3 (a), however when the inner jet has a high flow rate, the outer liquid is squeezed on the side walls and the interface accelerates the velocity inside the jet as it can be seen in figure 3 (b).

For each case, the Reynolds and Capillary numbers were computed using the following formulas:

\[ Re = \frac{\rho v D_h}{\eta_0} \]  \hspace{1cm} (2)

\[ Ca = \frac{\eta_0 v}{\sigma} \]  \hspace{1cm} (3)

\[ D_h = \frac{4A}{\rho} = \frac{4 \cdot jw \cdot h}{2jw + 2h} \]  \hspace{1cm} (4)

Reynolds number was computed using the hydraulic diameter, but in the case of jets, instead of using the total width of the microchannel \((w=400\mu m)\), the hydraulic diameter was computed using the jet...
widths for each case, along with the average velocity obtained from μPIV on a line away from the main microchannel entrance, where the jet is fully developed (as in the case of figure 3). The values of the non-dimensional numbers are displayed in Table 4.

| Liquid type / Capillary number / Reynolds number | Case I | Case II | Case III | Case IV | Case V |
|-------------------------------------------------|--------|---------|----------|---------|--------|
| Isopropyl alcohol                                | 0.08 / 0.97 | 0.124 / 1.66 | 0.136 / 1.9 | 0.14 / 1.97 | 0.146 / 2.08 |
| Ethanol                                          | 0.015 / 2.85 | 0.021 / 4.18 | 0.033 / 7.25 | 0.038 / 8.45 | 0.051 / 11.35 |

The first thing to notice from Table 4, is that only the Case I - IPA has the Re number below 1, in all the other cases the jets are influenced by inertial effects. For the Capillary number, the difference between the two types of alcohol is generated by the interfacial tension and it decreases as the velocity of the jet is increased.

Further phenomenon is observed in the case V, when the flow rate of the inner jet is increased as in figure 4. The interfacial tension between IPA and mineral oil is lower than in the case of ethanol and mineral oil. This in turn results in a three times higher Capillary number for IPA \((Ca=0.146)\). As the IPA jet enters the main microchannel, due to capillary action the IPA rises on the lateral branches of the microchannel and creates vortices. Another reason for this behaviour is the configuration of the microchannel that has an angle between the central branch and the side microchannels of 30°.

![Figure 3](image_url)  
**Figure 3.** μPIV velocity distributions on a horizontal line away from the entrance in the main microchannel for Case I a) and III b) presented in a non-dimensional form.

![Figure 4](image_url)  
**Figure 4.** Case V – interface rising, left IPA, right ETA
4. Conclusions

In this work we investigate alcohol type jets formation in a viscous outer liquid, in a steady state with no external perturbations. The low interfacial tension between the two immiscible liquid offers a precise control on the jet formation and as well the development of capillary action when the flow rate of the inner jet is higher. The advantage of using alcohol type jets is also the fact that the flow can be seeded and µPIV analysis can be performed. In the cases when the flow rate of the inner jet was higher, the interface squeezes out the outer liquid which in turn accelerates the interface and the lateral sides of the jet.

The light source has an important contribution to the interface visualization. In our case we can assume that the lower interfacial tension between IPA and mineral oil results in a better visualized interface with a thicker width. In the same setup, but with Ethanol, the interface is thinner as the interfacial tension between ETA and mineral oil is higher.

Further analysis has to be performed on the vortices created by capillary action with high speed cameras and as well µPIV.

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