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Solvent Shifting Approach for Droplet Generation in a Microfluidic Device

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ABSTRACT

A novel approach for microfluidic droplet generation via "solvent shifting" is presented in this paper based on an experimental investigation. In a 3D co-flow configuration with a jet of ethanol/oil mixture surrounded by water flow, the lateral diffusion leads to supersaturation followed by a phase separation and consequently formation of oil nanodroplets. Due to the solutal Marangoni effect the nanodroplets migrate inward and they get collected at the channel centerline. For high concentrations of the oil the density of the nanodroplets is so high that they can merge and produce microdroplets. If the mixture contains 10% oil, the average diameter of the produced microdroplets is within the range 10-30 μm for various jet flow rates. The size of microdroplets increases with the flow rate of the jet. Overall, for the first time we show that it is practical to generate microdroplets of different sizes by solvent shifting approach in a microfluidic setup.

KEYWORDS:

Droplet Generation, Microfluidics, Solvent Shifting, Ouzo Effect, Marangoni Convection.

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1- Introduction

Over the last decade an extensive effort has been put into research on droplet generation in microchannels which is related to the manifold applications of droplet microflows [1,2].

Microfluidic droplet generation has been conventionally based on hydrodynamic drag forces or surface-tension driven hydrodynamic instabilities. In such approaches the droplet size is closely linked to the microchannel dimensions, which are in turn restricted by fabrication technologies. Alternative methods in which the droplet size gets more independent of the channel dimensions help to overcome this problem.

Liquid/liquid extraction is a potential way to achieve this aim. In this process, by adding a non-solvent to a solvent/solute mixture, the solvent is extracted from the mixture and dissolved in the non-solvent. If the concentration of the solute is very low, a phase separation occurs in the form of the “Ouzo effect”. In such a process a huge number of very small droplets (i.e. about 1 μm or even smaller) form and stay in the system stably for several days without surfactant. Vitale and Katz [3] used divinylbenzene (DVB), ethanol and de-ionized water as the solute, the solvent and the non-solvent, respectively. They obtained an experimental ternary phase diagram (TPD) for this system in which the single-phase region, the stable ouzo region (where stable droplets form) and the unstable ouzo region (where spinodal decomposition occurs) are distinguished.

Using that TPD, recently we [4] performed an experimental/analytical investigation on formation and radial migration of DVB nanodroplets inside a microfluidic device with a 3D co-flow configuration. We showed that the nanodroplets move toward the center of the channel due to a solutal Marangoni convection and gather at the centerline. In the present article, some experimental results are presented which show that if the concentration of DVB is sufficiently high, the collection of DVB nanodroplets at the channel centerline results in the formation of microdroplets with sizes less than 50 μm.

2- Experiments, Results and Discussions

Figure 1 shows the schematic of the flow configuration in the microfluidic device. A tapered round glass capillary (nozzle) is inserted and fitted inside a square glass capillary. The inner and outer diameters of the nozzle are 30 μm and 50 μm, respectively. The width of the channel is about 1 mm.

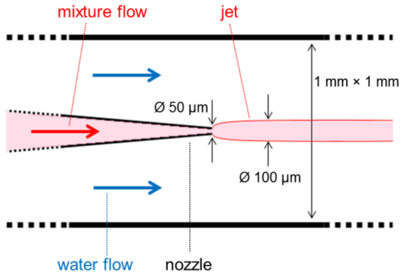

Figure 1. Flow configuration of the 3D co-flow microfluidic jet

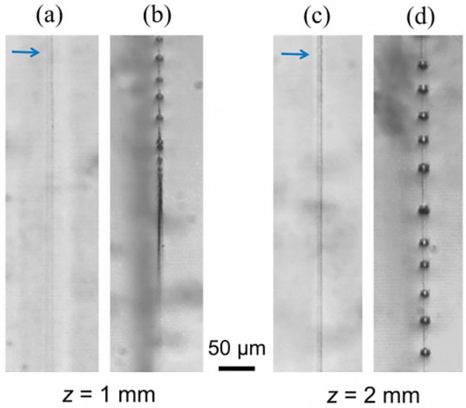

Figure 2. Effect of DVB concentration on droplet formation inside the channel. (a) and (c) correspond to 0.5 wt% DVB and 95.5 wt% ethanol, (b) and (d) to 10 wt% DVB and 90 wt% ethanol. The flow direction is upward. Arrows indicate the grey lines which show nanodroplets in the case of 0.5 wt% DVB

The schematic is shown horizontally; however, in reality it is arranged vertically since otherwise the jet deviates toward the top wall of the channel because the density of the mixture jet is smaller than that of water.

All experiments were performed at lab temperature (22-23^{o}C). In order to investigate the effect of DVB concentration on the droplet formation, two different concentrations of DVB are considered: 0.5 wt% and 10 wt%, both in binary solutions with ethanol.

Figure 2 shows that for high concentration of DVB (i.e. 10 wt%) microdroplets form, but for a very low concentration of DVB (0.5 wt%) no such droplets are visible. In the latter case, DVB nanodroplets are not individually visible but appear as grey lines at the center of the channel.

Figure 2 also compares these two cases at two different longitudinal positions along the channel (z). z is the distance from the nozzle and is related to the time via $z = V{\cdot}t$, where V is the fluid velocity in the vicinity of the channel centerline.

By increasing the jet flow rate (Q_{jet}) the jet diameter increases. Consequently the radial travel distance of the nanodroplets increases and it takes more time until a sufficiently high number of nanodroplets get collected at the channel centerline. As a result, the microdroplets form atlarger axial distances. Figure 3 displays the corresponding position (z_{drop}) in terms of jet flow rate. z_{drop} varies almost linearly with Q_{jet}.

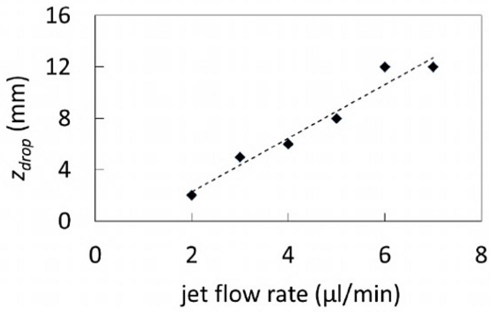

Figure 3. Position of microdroplet formation in terms of jet flow rate

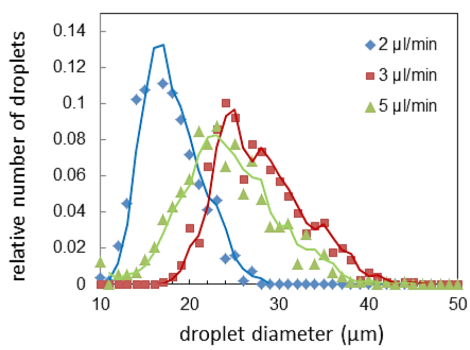

Figure 4. Size distribution of microdroplets for various Q_{jet} at z_{drop}

The size distribution of the microdroplets, i.e. the relative population of microdroplets in terms of the microdroplet diameter, is shown in Figure 4. These data correspond to z_{drop}.

In order to determine the size distribution, videos were recorded at z_{drop} for a certain time and were processed using the DMV software [5]. The software counted numbers and determined sizes of the microdroplets moving along the channel. By increasing Q_{jet} the amount of DVB in the system increases and consequently more DVB nanodroplets form and migrate inward. Therefore more nanodroplets coalesce, and consequently bigger microdroplets form.

After microdroplets have formed, they grow to some extent due to different mechanisms, e.g. adjacent microdroplets coalesce. Thus, the average size of the microdroplets increases, and their number decreases while moving along the channel (Figure 5).

3- Conclusions

We presented a new approach for generating droplets in a microfluidic device, based on radial mass transfer between a laminar liquid jet and its surrounding in a ternary liquid system. This method benefits from two key features. Firstly, solvent shifting results in the formation of solute nanodroplets and secondly, the solutal Marangoni effect forces nanodroplets to gather and merge at the channel centerline. That way, almost monodisperse droplets of tens of micrometers diameter form.

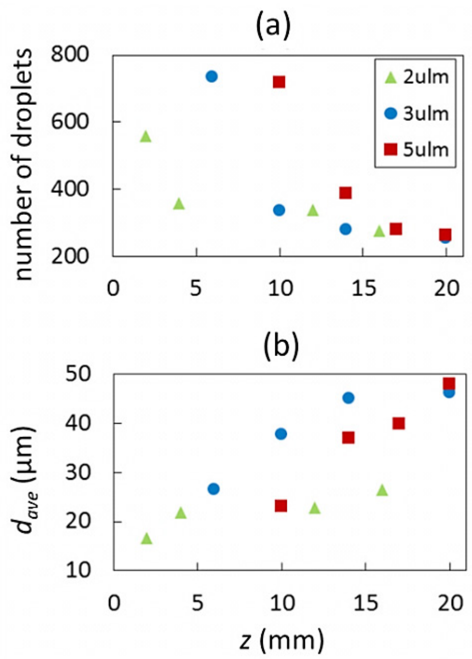

Figure 5. Change of number (a) and average size (b) of droplets along the channel

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