μPIV Study of Passive Droplet Generation in a T-junction in the Squeezing, Transition, and Dripping Regimes

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Abstract Results are presented from micro particle image velocimetry (μPIV) studies of passive droplet generation in a T-junction microchannel operating in the squeezing, transition and dripping regimes. The μPIV studies were done on the dispersed phase at filling and start of pinch-off stages for all examined regimes. Within the limitations of our μPIV system a three dimensional velocity map of the velocity profile along the droplet height was recorded for each examined droplet phase. Furthermore, the effect of adding a surfactant Sodium dodecyl sulfate (SDS) above the critical micelle concentration (CMC) was examined for the studied regimes with matched capillary number (Ca). An external droplet detection system was used to detect the droplet phase and was used to trigger the μPIV image acquisition system. This approach allowed image acquisition of different droplets at the same location and condition for a steady droplet generation operational regime. Experimental results indicate that both squeezing and transition regimes share many similarities in their velocity profile in both filling and start of pinch-off phases. At the planes closer to the channel walls the flow field in the droplet phase is dominated by the contact with the lubrication region of the droplet and the maximum velocity occurs close to the channel gutter region. At the mid-plane the velocity field in the squeezing and transition regime differed where high velocity regions were noticed for the transition regime compared to the squeezing regime. This pattern is indicative of the nature of the acting shear force that is present in the transition regime. Droplet generation in the examined dripping regime differed from the squeezing and slightly from transition regime. During the filling stage of the dripping regime the maximum velocity regions are located at the middle plane of the channel. These patterns are indicative of the high shear that acts on the interface of the droplet phase. Droplet pinch-off in the dripping regime differs from the squeezing and transition where the pinch-off occurs downstream of the T-junction. Also, pinch-off starts with the thinning of the liquid thread close to the top and bottom walls and propagates to the middle region. Finally, the presence of a surfactant above the CMC concentration did not have an effect on the general velocity patterns for the examined droplet generation regimes as long as Ca was matched. However, the magnitude of the velocities differed for fluid conditions with a surfactant.

1. Introduction

Passive generation of a liquid segment in a carrier fluid in a micro-scale structure has received much attention in the past 10 years. This attention is attributed to the many advantages that it offers such as: ease of generation, monodispersity, pure isolation of segments, adequate control of size and speed of segments, and high generation rate (up to kHz) (Berthier, 2013; Christopher et al., 2008). A geometry that is commonly used as a segment generator is T-junction design. Usually, in T-junction microchannel design the carrier fluid is pumped in the main stream of the T-junction while the dispersed phase is pumped through the side channel. One property that must be assured for stable droplet generation is that the continuous phase wets the channel material more than the dispersed phase (Christopher et al., 2008).

It has been reported that there are three main regimes for stable droplet generation in a T-junction: squeezing, transition, and dripping (Fu et al., 2010; Xu et al., 2008). The distinction between these is the type of force that causes pinch-off of a fluid segment.). The segment generation regimes as identified by Xu et al. (2008) are: squeezing Ca < 0.002, transition 0.002 < Ca < 0.01, and dripping regime 0.01 < Ca < 0.3. Most experimental studies of droplet generation utilize bright field microscopy with high speed video recording to find correlations that describe the generation process (Christopher et al., 2008; van Steijn et al.,
2010). A number of correlations have been published in the literature that attempt to predict droplet size in different regimes of droplet generation (Christopher et al., 2008; van Steijnen et al., 2010).

Also from the literature, quantitative studies of droplet generation in a T-junction microchannel with µPIV have shown interesting results regarding the flow patterns that exist during the generation process. van Steijnen et al. (2007) examined generation of bubbles in T-junction design with a µPIV system. In their work they used ethanol as the continuous phase and air as the dispersed phase. Their results revealed that at the start of pinch-off there will be a reverse flow at the interface of the soon to be trailing edge of the bubble. This sudden change in the flow of the continuous phase is also a reason for the fast and rapid pinch-off of a liquid segment.

Malsch et al. (2010) studied the effect of the existence of pressure compliance in the fluid source connections that fed solutions in a T shaped nozzle. Their results indicate that an elastic tube causes pressure to build up of the droplet phase before reaching a critical pressure and bursting inside the main stream channel. Also, after pinch-off they showed there is a circulation zone that starts at the trailing edge of newly formed droplets. Oishi et al. (2009) presented three dimensional velocity patterns in a droplet during the droplet generation process in a T-junction. Their results show that complex flow patterns exist in both the continuous and dispersed phase at different Capillary number (Ca = u_{avg} μ / γ, where u_{avg} is the average velocity, μ is the fluid viscosity, and γ is the interfacial tension between the fluids). To our knowledge most µPIV studies of droplet generation in T-junctions were performed in the squeezing regime. This is due to the challenges in examining droplet generation phases at the transition or dripping regimes and with µPIV it is very difficult because of many hardware challenges. For example, high speed imaging cannot be used since CMOS based cameras require long exposure duration (Hain et al., 2007). On the other hand, dual frame CCD cameras need a fast and reliable triggering system to phase-lock different droplets at certain stages (Lindken et al., 2009; van Steijnen et al., 2007).

In this work µPIV studies of droplet generation in the squeezing, transition, and dripping regimes in a T-junction microchannel will be presented. Experiments were performed for two combinations of fluids: without a surfactant or with a surfactant. The fluid of focus was the dispersed phase (droplet phase) during the filling and start of pinch-off stages. The velocity fields at different planes of the droplet were examined to find the three dimensional flow patterns inside the droplet and how the patterns differ in different droplet phases. Details about the materials used, experimental setups, and experimental approach will be discussed next.

2. Sample Fabrication and Materials

2.1 Channel Fabrication

Channels were fabricated from PDMS with the soft-lithography approach which is well known in the microfluidics community (Ng et al., 2002). Channel designs had two main parts: a T-junction for droplet generation and two waveguides that were used to guide and align two optical fibers that were used for the droplet detection system, as will be discussed later. The main channel width was w_c = 200 μm and the side channel width was w_d = 140 μm. The height of the PDMS design was h = 148 μm. Fig. 1 presents a schematic of the design used in the current work and an actual PDMS channel used in experiments.

2.2 Fluids

The fluids that were used in examining droplet generation with the µPIV were silicone oil (10 cSt, Sigma Aldrich), water, and glycerol. Silicone oil was chosen as the continuous phase since it wets hydrophobic PDMS. A mixture of water and glycerol was used as the dispersed phase. Glycerol was mixed with water with a mass ratio of 52 % to closely match the refractive index of silicone oil and PDMS. There were two types of water glycerol mixture that were used which were with or without a surfactant. The surfactant that was used was Sodium Dodecyl Sulfate (SDS, Sigma Aldrich) and it was added with a concentration of 0.57 % w/w. The main desired function of SDS is to lower the interfacial tension between the water-glycerol
mixture and silicone oil where the interfacial tension without surfactant was $\gamma = 33.2$ mN/m and with surfactant $\gamma = 12.2$ mN/m. Polystyrene fluorescent particles with a diameter of 1 µm (Fluospheres 535/573, Invitrogen) were added to the dispersed phase used in each experiment. The particle concentration in the dispersed phase was 0.03 % v/v.

2.3 Experimental Setups

There were two experimental systems that were used in this work: droplet detection, and the µPIV system. These two systems were assembled in a way that the droplet detection system serves as an external trigger for µPIV image acquisition. Details about the main parts of each system are presented next.

2.3.1 µPIV system

The µPIV system consists of an dual head Nd:YAG laser (ESI) as a light source, a dual frame CCD camera C8484-05CP (Hamamatsu), Nikon Ti-E Eclipse equipped with a 20X objective lens and a 0.5X adapter for the camera, and a MotionPro (IDT Vision) Timing hub. Image acquisition and analysis was done with Dynamic Studio V2.3 (Dantec Dynamics).

2.3.2 External Triggering System

Since it is impossible to capture a large number of images for one droplet and then average results we rely on averaging images of different droplets formed under the same condition and acquired at the same phase. This was assured with a droplet detection system that works with a different wavelength than what is recorded by the CCD camera. Droplet detection is achieved by guiding an IR 780 nm light via a single-mode fiber (stripped to its cladding diameter of 125 µm) towards an area of interest. A multi-mode fiber is aligned opposite to the single mode fiber and serves as a light collector and transfers light to a PMT (Hamamatsu). Changes in the transmitted light occur when droplets pass through the area of interest and sensed by the PMT which is then converted to a voltage signal that triggers the µPIV system. A delay circuit was sometimes used to impose a delay on the signal from the trigger in order to capture droplets at different phases of development.

2.4 Experimental Methodology

All experiments were performed with a high precision syringe pump (Pump 33, Harvard Apparatus). An experiment starts with pumping silicone oil in the microchannel network for at least 30 minutes. This process primes the chip in order to assure proper wetting of silicone oil on the PDMS walls of the microchannel prior to introducing the dispersed phase. Afterwards, the water-glycerol mixture containing 1 µm fluorescent particles is introduced via the side channel of the T-junction (see Fig. 1). In all experiments the flow rate of the dispersed phase (water-glycerol) was 25 % of the silicone oil flow rate. This value was set to assure the generation of small droplets that could be observed in the field of view.

The acquired images were analyzed with an adaptive correlation approach with Dynamic Studio (v2.3, Dantec Dynamics). A 32 X 32 pixel interrogation area was used. A peak validation scheme was applied to the results from the adaptive correlation. Afterwards, a coherence filter with a width of 31 pixels was applied to the peak validated results. The final step of analysis was to perform statistical averaging of filtered results.
Fig. 1: A schematic of the design used in the current work with an image of the PDMS microchannel connected to the tubing and fiber optics. Figure (a) Schematic illustration of the channel design used in the current work, (b) The PDMS channel used in the current study mounted on the microscope stage. The parts presented in figure (b) are: 1- The PDMS microchannel, 2- Single mode fiber, 3- Multimode fiber, and 4- Teflon tubing used to supply the fluids from the syringe pump.

3. Results

In the current study three droplet generation regimes were examined with a focus on the filling stage and start of pinch-off. These regimes were squeezing (Ca = 0.001), transition (Ca = 0.005), and dripping regime (Ca = 0.02) for two fluid conditions without and with SDS. The droplet filling stage is presented first for the squeezing regime Ca = 0.001 for fluid combinations with and without a surfactant. Fig. 2 presents the upper half of the obtained three dimensional velocity vector plots for the filling stage of the squeezing regime.

Fig. 2: Three dimensional velocity vector plot in the squeezing regime Ca = 0.001 for water-glycerol without and with SDS. Figures are: (a) Water-glycerol without SDS, and (b) Water-glycerol with SDS. The velocity magnitudes are in m/s.

From the results shown in Fig. 2 it is clear that the velocity has different profiles at different planes. For planes closer to the upper wall of the channel the maximum velocity is located at the edge of the liquid/liquid interface which is the region of gutter flow. The gutter region is subjected to the flow of the continuous phase that is flowing past the droplet. As a result of this high shear is expected on the droplet phase at the gutter region compared to the bulk droplet interface exposed to the lubrication region at the top wall.

Closer to the middle of the channel the projected area of the droplet increases. This was clearly shown in Fig.
2 (a) and (b). The velocity profile in the middle plane differs from what was observed in the squeezing regime. The bulk maximum velocity occurs at the back region of the droplet phase before the droplet reaches the side wall. One observation was that the presence of surfactant did not have an effect on the velocity patterns for the different planes of the squeezing regime. The effect of the presence of surfactant was manifested on the magnitudes of the velocities for different droplet planes where the effect of surfactant reduced the magnitudes of the velocities. The magnitude of reduction is related to the interfacial tension ratio between the two fluid conditions (without and with SDS).

The droplet pinch-off in the squeezing regime was examined for the two fluid conditions and the general velocity patterns were similar. An example of the velocity patterns for the fluid condition without surfactant for the top, middle and bottom planes at the start of droplet pinch-off is presented in Fig. 3.

![Fig. 3: The velocity vector plots at different planes at start of droplet pinch-off in the squeezing regime for the experiment of fluids without a surfactant. The upper images indicate the overall velocity field during start of pinch-off at different planes. The bottom images focus on the velocity vector plots at the T-junction. The location of each plane is indicated on the image. The velocity magnitudes are in m/s.](image)

The patterns that are shown in Fig. 3 were, approximately, for the upper, middle and lower planes of the channel. For the upper and lower planes (z = 20 and 120 µm) the location of the maximum velocity is close to the edge of the liquid interface in contact with the gutter region. In contrast for the middle plane (z = 70 µm) the region with the maximum velocity occurs at the middle plane close to the corner of the T-junction. This is due to the fact that with the squeezing of the interface the velocity becomes high close to the entrance. The lowest velocities at the mid-plane were located at the regions where the droplet phase is in contact with the side walls of the channel.

Examination of the velocity vector plots at the corner of the T-junction (second row of Fig. 3) it can be noticed that at the top and bottom planes (z = 20 and 120 µm) there is more disturbance in the vector fields. This is indicative that the pinch-off starts at the top and bottom planes and propagate towards the middle plane. On the other hand the middle plane (z = 70 µm) showed a smoother velocity profile close to the corner compared to the top and bottom planes.

The examination of the filling stage of the transition droplet generation regime with Ca = 0.005 was performed for the two fluid conditions: without and with SDS. There were no major differences in the general velocity patterns for both fluid conditions in the transition regime. An example of a section of the three dimensional velocity patterns for the generation in the transition regime is presented in Fig. 4.
Fig. 4: Three dimensional velocity vector plot in the squeezing regime Ca = 0.005 for water-glycerol with SDS. The velocity magnitudes are in m/s.

It is clear that velocity patterns in the transition regime differ from the squeezing regime. This was clear since the maximum velocity occurred at the middle plane of the microchannel. Thus, the flow of the continuous phase close to the side wall is higher in the condition of the transition regime. This indicates the effect of shear playing a role in the droplet generation in the transition regime. The droplet pinch-off stages for the generation in transition regime is presented in Fig. 5.

Fig. 5: Velocity vector plots at different stages of droplet generation in the transition regime (Ca = 0.005) for the middle plane (z = 70 µm) and lower plane (z = 20 µm). The velocity magnitudes are in m/s.
From Fig. 5 it is evident that the stage prior to droplet pinch-off in the transition regime shares similarities with the squeezing regime (see results of the mid plane in Fig. 3). The start of squeezing forces on the liquid interface close to the corner reduces its thickness leading to an increase of the velocity of the dispersed phase close to the T-junction. Immediately after pinch-off the droplet velocity vector plot showed interesting results as shown in Fig. 5 (b). The region of the maximum velocity is located at the trailing edge of the droplet. This is due to the fact that interface reformation is very rapid since the droplet interface needs to connect with droplet body and have a curved trailing edge. Thus the speed of the interface is very high compared to other stages of the droplet formation. After the droplet shape reforms the maximum velocity region of the droplet at the middle plane is located at the center of the droplet body, as shown in Fig. 5 (c). The velocity vector plots for droplet pinch-off in the transition regime at the lower plane ($z = 20 \mu m$) shown in the lower row part of Fig. 5 present interesting results. First at the start of pinch-off the velocity patterns are similar to what was observed in the squeezing regime (Fig 3 upper and lower planes). Immediately after pinch-off the velocity patterns at the bottom plane are similar to the middle plane for the same phase. The similarity was that the trailing edge of the droplet has the highest velocity. After the droplet reforms to its final shape the maximum velocity regions are located at the trailing and leading edge of the droplet.

The third droplet regime that was examined was the dripping regime with $Ca = 0.02$. The velocity vector plots of the filling stage for the dripping regime were similar to what was observed in the transition regime with $Ca = 0.005$ (Fig. 4). The maximum velocity regions were observed in the region close to the wall. The main difference for the dripping regime was observed in the droplet pinch-off stage where droplet pinch-off occurred downstream of the T-junction. Moreover, droplet pinch-off started with a thinning of the droplet phase thread close to the top and wall channels and propagated towards the middle plane. An example of the start of droplet pinch-off in the dripping regime is presented in Fig. 6.

From Fig. 6 (a) it is clear that the maximum velocity region occurs at the middle plane of the channel. This pattern is expected in the dripping regime since the droplet formation for this regime is subjected to the high shear of the continuous phase. The absolute maximum velocity also occurs at the middle plane of the dripping regime. At slightly higher planes ($z = 110 \mu m$) the projected area of the droplet decreases indicated that there is thread detachment. This thread detachment indicates the start of detachment of a droplet. The velocity patterns at this plane indicate that maximum velocity region is located at the liquid/liquid interface close to the side wall (gutter region). The previous discussions for the velocity vector plots in the squeezing and transition regimes for the planes close to the extreme walls are applicable for the dripping regime. Mainly, the maximum velocity regions are located close to the gutter region of the liquid flow, as seen in Fig. 6 (c).

4. Conclusions

A µPIV system was used to study droplet generation in a T-junction in the squeezing, transition, and dripping regimes for fluid combinations with and without surfactant. The study focused on the filling stage and start of pinch-off. An examination of the changes of the velocity patterns across the different planes of
the microchannel was done. The velocity patterns at extreme planes (close to the top and bottom walls) were similar for the different droplet regimes. At those planes the flow at the gutter region close to the corner affects the velocity of the droplet phase creating a maximum velocity at that region. This was shown for both the filling and start of droplet pinch-off.

The other important plane that was examined was the mid-plane of the T-junction. Results at the mid-plane indicate that the transition and dripping regimes share many similarities in the velocity patterns during both filling stages. The start of pinch-off was similar between the squeezing and transition regimes where a disturbance in the velocity patterns started at the planes close to the top and bottom walls and propagated to the middle plane. The droplet pinch-off in the dripping regime differs in that the dispersed liquid thread moves inside the main stream channel and then pinches off. This shifting in the location of the thread changes the velocity patterns at the different planes prior to pinch-off for the dripping regime compared to the squeezing and transition regimes.

References


