μFLU12-13

DISPERSED PHASE VELOCITY CONTROLLED REGIME OF MICRO-DROPLETS GENERATION IN T-JUNCTION

Nathalie TARCHICHI, Franck CHOLLET*, Jean-François MANCEAU
FEMTO-ST Institute, Université de Franche-Comté,
32 avenue de l'Observatoire, 25044 Besançon, FRANCE
nathalie.tarchichi@femto-st.fr, franck.chollet@femto-st.fr, jfmanceau@femto-st.fr

KEY WORDS

T-junction, dispersed phase, velocity, droplet generation, liquid-liquid system

ABSTRACT

We present an experimental study of the effect of the dispersed phase velocity on the regime of droplet generation in a T-junction microfluidic configuration. Silicone oil with a large interfacial tension (100 mN/m) was dispersed in deionized water. In addition to the known regimes of droplet generation (dripping, squeezing and jetting regimes), we present a new regime of monodisperse droplet generation that we named balloon regime. This regime appears to be linked to the injection of the dispersed phase at lower velocity through a narrow channel. In our experiments, the velocities of the continuous and the dispersed phases $\overline{v}_c$ and $\overline{v}_d$ respectively, have been varied in a wide range: $\overline{v}_c$ from 0.93 to 50 cm/s, and $\overline{v}_d$ from 0.01 to 3 cm/s. In this new regime, the diameter of the micro-droplets generated is constant and is not related to the velocity of the continuous phase, which just acts as the carrier of the micro-droplet. A comparison between the balloon and the dripping regimes is presented. In the balloon regime and contrary to the dripping regime, the droplet formed keeps a circular shape throughout its formation at the T-junction, without any deformation due to drag forces. To explain the formation of the micro-droplets in the balloon regime, we propose a mechanism based on the stability of the micro-droplets shape.

1. INTRODUCTION

Liquid-liquid dispersions in microfluidic systems have drawn attention in the last few years for different applications in science and technology [1]. The generation of droplets is performed using various microfluidic structures such as T-junction [2], flow-focusing [3], or co-flowing devices [4]. These configurations have been proposed by several authors in order to generate monodisperse droplets. For many applications, in addition to the size, the shape and the formation mechanism of the droplets are also critical parameters.
In the T-junction configuration, three main regimes of droplet generation have been reported: squeezing, dripping and jetting regimes [5], [6], [7]. In the squeezing regime, the droplet formed has an elongated shape and a length larger than the width of the continuous phase channel. Whereas in the dripping regime, the droplet generated is smaller than the width of the continuous phase channel. In the jetting regime, the dispersed phase forms a long neck in the continuous phase channel and the break-up in droplets occurs later in the channel. This regime usually leads to the formation of droplets

* Corresponding author

of small size, but it quickly becomes unstable when the droplets generated become very small compared to the width of the continuous phase channel. The conditions leading to these different regimes are governed by the value of the capillary number of the continuous phase, reflecting the ratio between the shear force and the interfacial force at the junction. For constant interfacial tension and viscosity, the control parameter is simply the continuous phase velocity.
In the present study, we explore the effect of the dispersed phase velocity, and show the presence of a new regime of monodisperse droplet generation. In this regime the droplets generated have a constant size, smaller than the width of the continuous phase channel, and independent of the dispersed and the continuous phase velocities, unlike the three other known regimes in which the droplet size is a function of the flow rates of the continuous and dispersed phases [5], [6], [7].
Actually, we can find in the literature a few examples of droplet generator, where the droplet remains spherical during its formation. For example, Sugiura et al. used a microfabricated 3D channel array, in which the break-up of the droplet is related to a pressure drop when the channel depth changes [8]. In our system, we used a classical 2D geometry (T-junction) and the phenomena involved in the break-up is completely different.

2. MICROFLUIDIC DEVICE

A dispersion of oil in water is produced using a T-junction configuration (Figure 1).

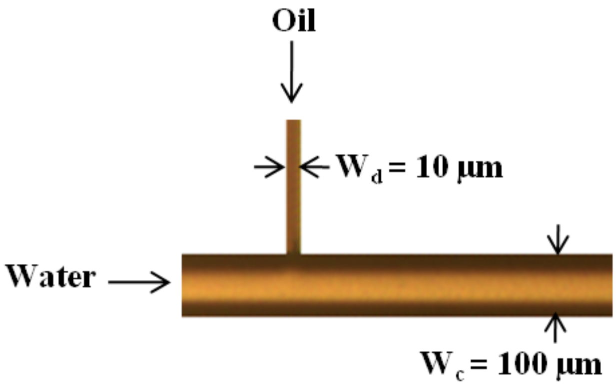

Figure 1: Schematic of the T-junction system used in the generation of micro-droplets.

Photolithography, DRIE etching and anodic bonding techniques were used for fabricating channels in silicon with a Pyrex glass cover. The dispersed phase and the continuous phase channel have a width of 10 µm and 100 µm, respectively, and both have a depth of 72 µm. This microfluidic device was fabricated in the clean room of the FEMTO-ST Institute.
Silicone oil (Dow Corning 704® with kinetic viscosity of 39 cst, and a density of 1070 kg/m^3) was used as the dispersed phase and deionized water with a blue dye was used as the continuous phase, resulting in an interfacial tension of 100 mN/m as measured by a KRÜSS tensiometer. This high value of the interfacial tension is probably due to the use of ultra pure oil. Actually, the higher the purity of the fluid, the higher the interfacial tension [9].
Two syringe pumps were used to inject liquids and control the flow rates of the continuous and dispersed phases in the micro-channels. Micro-droplets diameter was measured using a microscope and a CCD camera with a high speed shutter. All experiments were realized at a constant temperature (20 ± 2°C).

3. RESULTS AND DISCUSSION

In this work, we show the effect of the dispersed phase velocity on the regime of droplet generation in a T-junction microfluidic system. The dispersed phase velocity $\overline{v}_d$ was varied from 0.01 to 3 cm/s,

and the continuous phase velocity $\overline{v}_c$ was varied from 0.93 to 50 cm/s (corresponding to 9.3 x 10^{-5} < Ca < 5 x 10^{-3}) .
We have observed that the regime of micro-droplet generation changes according to the velocity of the dispersed phase, and it passed from the dripping regime ($\overline{v}_d = 3$, 1.5 and 0.75 cm/s) to a new regime of droplet generation in which the micro-droplet size is constant whatever the values of $\overline{v}_d$ ($\overline{v}_d \leq 0.6$ cm/s). We call this new regime the balloon regime because, as we will see later, the swelling of the droplet resembles an inflating balloon.
Figure 2 shows this dramatic change of the droplets generation regime based on the value of the dispersed phase velocity. In the dripping regime, the micro-droplet diameter d decreased when the dispersed phase velocity $\overline{v}_d$ decreased, and when the continuous phase velocity $\overline{v}_c$ increased. But in the balloon regime the micro-droplet diameter is constant and independent of the dispersed and the continuous phase velocities. In the balloon regime, the dispersed phase flow rate affects only the frequency of the micro-droplet generation (Figure 3), while the continuous phase flow rate changes the velocity of the micro-droplets in the continuous phase micro-channel.

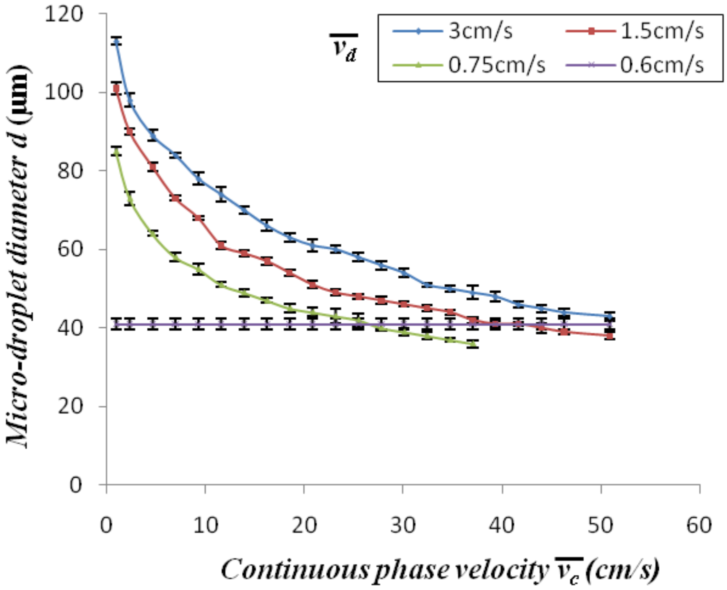

Figure 2: Effect of the dispersed phase velocity on the micro-droplet diameter.

Figure 4 shows the droplets generated for different dispersed phase velocity, for a continuous phase having a velocity of 0.93 cm/s (corresponding to the smallest $\overline{v}_c$ value in Figure 2). For the first three Figures (a, b and c), we are in the dripping regime, and the droplet diameter is a function of the dispersed phase velocity. The last two Figures (d and e) show the balloon regime where the droplet diameter is clearly independent of the dispersed phase velocity.

4. MECHANISM OF DROPLET GENERATION: COMPARISON BETWEEN DRIPPING AND BALLOON REGIMES

4.1 Dripping regime

In the dripping regime, the formation process of the droplet occurs in three main stages [10](Figure 5):
-Stage I: Arrival of the dispersed phase in the T-junction
The droplet formation process starts when the oil reaches the T-junction at $t = t_0$. Then the oil enters the continuous phase micro-channel, and starts forming a circular shape. At the end of this stage at $t = t_I$, the size of the droplet formed is only related to the width of the dispersed phase micro-channel w_d. Actually, the droplet has a circular shape, and forms an angle θ_I with the walls of the continuous

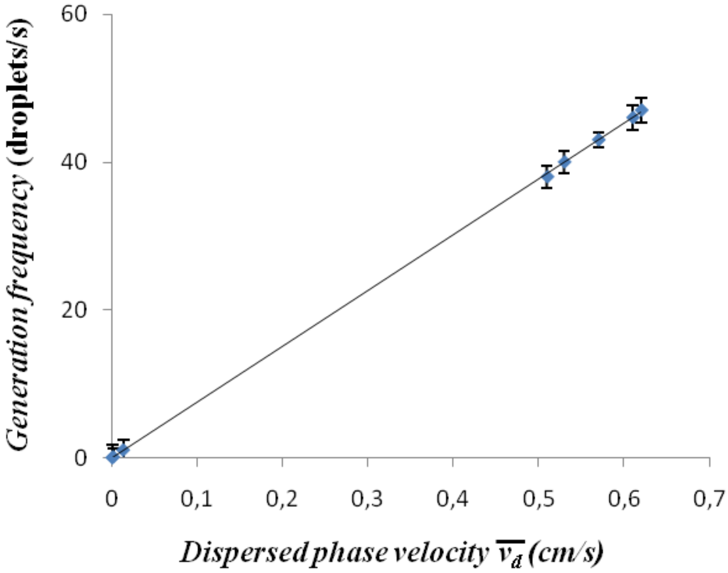

Figure 3: Frequency of droplet generation as a function of the velocity of the dispersed phase in the balloon regime.

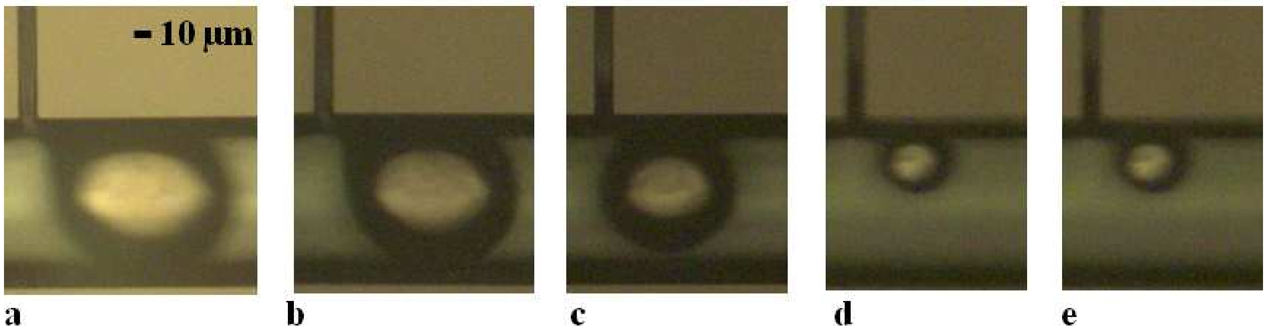

Figure 4: Regime of micro-droplets generation for different values of the dispersed phase velocity (a, b, c) dripping regime and (d, e) balloon regime with $\overline{v}_c$ = 0.93 cm/s, $\overline{v}_d$ = 3 cm/s (a), 1.5 cm/s (b), 0.75 cm/s (c), 0.6 cm/s (d), 0.01 cm/s (e) and d = 113 µm (a), 101 µm (b), 85 µm (c), 41 µm (d, e).

phase micro-channel. This angle depends on the velocity of the dispersed phase $\overline{v}_d$. When $\overline{v}_d$ is higher, the droplet deformation occurs earlier, θ_I is higher, and the transition to the stage II is faster.
Once the droplet loses its circular shape and starts deforming, the stage II begins.
-Stage II: Swelling of the droplet
During this stage, the droplet deforms and inflates before it detaches, and its shape is maintained by an equilibrium between the surface tension and the drag force composed of a pressure force and a shear force. At the end of this stage, and just before the start of detachment at $t = t_{II}$, the droplet formed is tangent to the left edge of the dispersed phase micro-channel. At this time, the droplet has deformed to reduce the drag, dominated by pressure force (shear force is smaller due to the lower viscosity of water). The section S of the droplet is mostly governed by the velocity of the continuous phase $\overline{v_c}$, and the width of the continuous phase micro-channel w_c, but independent of the dispersed phase micro-channel geometry. As w_c and $\overline{v}_c$ are constants, the section S of the droplet at $t = t_{II}$ is constant in the experiments.
-Stage III: Droplet detachment
After $t = t_{II}$, the droplet starts detaching from the left edge of the dispersed phase micro-channel, and moves rapidly to the right closing the flow of oil into the droplet. The direction of detachment of the droplet is determined by the direction of water flow. The swelling of the droplet during this phase,s,

is related to the dispersed phase flow and can be expressed by:

$$s = \overline{v}_d w_d (t_{III} - t_{II}) \tag{1}$$

In our experiments, S is constant and the time required to close the flow of oil is constant. As w_d is constant, s is only related to $\overline{v}_d$. Actually, s increased when $\overline{v}_d$ increased as we see in Figure 4 (a, b and c).
At the end of this stage at $t = t_{III}$, the droplet is detached and a new cycle of droplet generation starts.

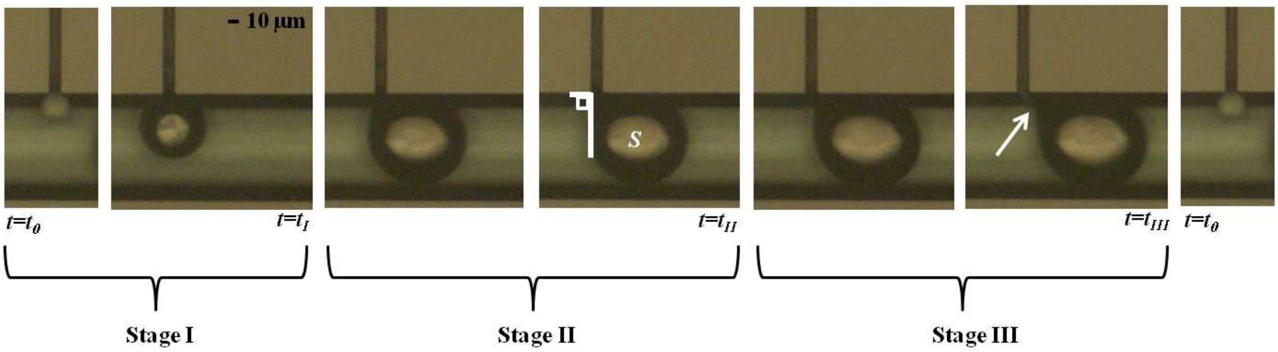

Figure 5: Detachment mechanism of the droplet in the dripping regime with $\overline{v_d}$ = 3 cm/s µm and $\overline{v_c}$ = 0.93 cm/s.

4.2 Balloon regime

In this regime, the micro-droplet is generated at the intersection of the two channels, and forms a circular shape. Then the micro-droplet formed moves into the continuous phase micro-channel in the direction of the water stream (Figure 6).

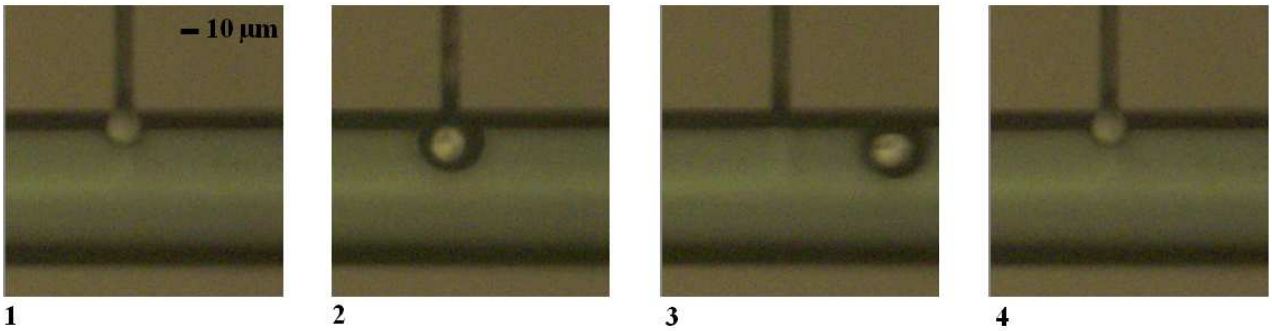

Figure 6: Mechanism of micro-droplet formation in the balloon regime.

Actually, the micro-droplet generation process starts when the dispersed phase arrives at the T-junction, enters the continuous phase micro-channel and starts forming a circular shape. A similar step is present at the beginning of the dripping regime (stage I in Figure 5). In the balloon regime, and contrary to the dripping regime, the micro-droplet continues its swelling without any deformation before it detaches. In other words, the inflating micro-droplet remains continuously in stage I. The origin of this behavior is thought to originate from the structural stability of the micro-droplet cylindrical shape compounded with the large interfacial tension present in our experiments. The arrival of the dispersed phase at low velocity can not induce deformation of the droplet, which maintains its circular shape throughout its growth. In the dripping regime, the velocity of the dispersed phase is higher and the larger momentum deforms the micro-droplet which becomes unable to resist the lateral drag force exerted by the continuous phase flow, finally inducing a transition to stage II.

When the micro-droplet inflates, the angle θ between the micro-droplet and the wall of the continuous phase micro-channel decreases. Because of the continuity of the interface between oil and water, this decrease results in the apparition of a water bulge on both side of the stream in the dispersed phase micro-channel (Figure 7). When the induced side bulges finally meet in the dispersed phase micro-channel for $\theta = \theta_{min}$, the micro-droplet detaches. This angle θ_{min} depends mainly on the width of the dispersed phase micro-channel w_d. In some way the suggested mechanism resembles the capillary instability phenomenon.
Then the continuous phase transports the micro-droplet in the continuous phase micro-channel and a new cycle of micro-droplet generation starts [11].

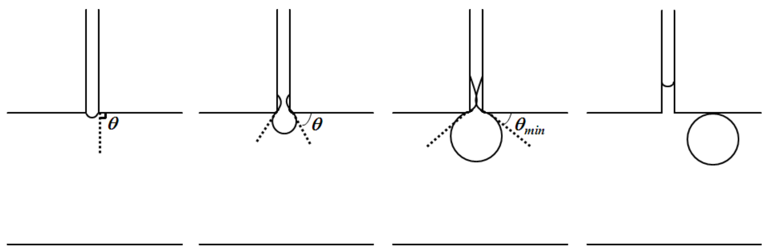

Figure 7: Schematic of the micro-droplet detachment in the balloon regime.

5. CONCLUSION

In this study, we present the effect of the dispersed phase velocity on the regime of droplet generation and show the presence of a new regime of oil in water micro-droplet generation named balloon regime observed at lower values of the dispersed phase velocity. A T-junction device made on silicon-Pyrex was fabricated in the clean room. The continuous and the dispersed phases micro-channels have a width of 100 µm and 10 µm respectively, and a depth of 72 µm. We show that the regime of micro-droplet generation changes according to the velocity of the dispersed phase. It passed from the dripping regime for $\overline{v}_d \geq 0.75$ cm/s to the balloon regime for $\overline{v}_d \leq 0.6$ cm/s. The particularity of the balloon regime, that differentiates it from all other known regimes can be summarized in two points. First, the size of the droplets generated is constant and does not depend on the continuous phase velocity as observed with all other regimes of droplet formation. Second, the droplet keeps a circular shape throughout its formation at the T-junction, without deformation due to drag forces. We finally proposed a mechanism explaining the generation of droplet in the balloon regime based on the stability of the micro-droplet shape and compared it with the mechanism of droplet generation in the dripping regime.

6. FUTURE WORK

In the future, we will study microfluidic devices with different cross-sections (depth and width) of the continuous phase and the dispersed phase micro-channels in order to clarify the behavior of the micro-droplets formed in the balloon regime, and prepare a quantitative model.

REFERENCES AND CITATIONS

[1] Whitesides G. M. (2006). The origins and the future of microfluidics. Nature, 442, 368-373.
[2] Thorsen T. & Roberts R.W. & Arnold F.H. & Quake S.R. (2001). Dynamic pattern formation in a vesicle-generating microfluidic device. Phys. Rev. Lett, 86, 4163-4166.
[3] Gañán-Calvo A. M. & and Gordillo J. M. (2001). Perfectly Monodisperse Microbubbling by Capillary Flow Focusing. Phys. Rev. Lett, 87, 274501.
[4] Umbanhowar P. B. & Prasad V. & Weitz D. A. (2000). Monodisperse Emulsion Generation via Drop Break Off in a Coflowing Stream. Langmuir, 16, 347-351.

[5] Cubaud T. & Mason T. G.(2008). Capillary threads and viscous droplets in square microchannels. Physics of Fluids, 20, 053302.
[6] Christopher G. F. & Noharuddin N. N. & Taylor J. A. & Anna S. L. (2008). Experimental observations of the squeezing-to-dripping transition in T-shaped microfluidic junctions. Physical Review E, 78, 036317.
[7] Sivasamy J. & Wong T-N. & Nguyen N-T. & Kao L. T-H. (2011). An investigation on the mechanism of droplet formation in a microfluidic T-junction. Microfluid Nanofluid, 11, 1-10.
[8] Shinji S. & Mitsutoshi N. & Satoshi I. & Minoru S. (2001) Interfacial tension driven monodispersed droplet formation from microfabricated channel array. Langmuir, 17, 5562-5566
[9] Dopierala K. & Javadi A. & Kragel J. & Schano KH. & Kalogiannid E. & LeserM. & Miller R. (2011) Dynamic interfacial tensions of dietary oils. Colloids Surf A, 382, 261-265
[10] Tarchichi N. & Chollet F. & Manceau J.F. (2012). T-Junction cross-section geometry influence on oil in water micro-droplets diameter.submitted.
[11] Tarchichi N. & Chollet F. & Manceau J.F. (2012). New regime of droplet generation in a T-shape microfluidic junction. Microfluid Nanofluid. DOI 10.1007/s10404-012-1021-8.