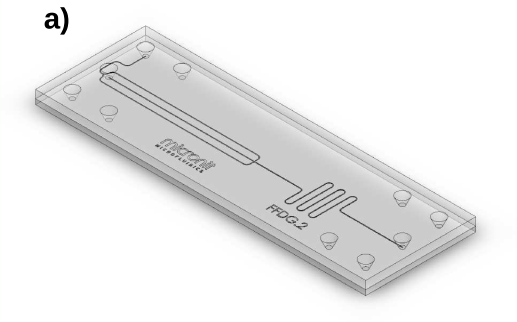
Microfluidic droplet generators

1 Summary

1.1 Droplet generator chips

Micronit offers two types of droplet generator chips with a channel width and depth of 100 µm and 20 µm respectively (see Fig. 1). Both the Focused-Flow Droplet Generator chip (FC_FFDG.2) and the T-Shaped Droplet Generator chip (FC_TSDG.2) rely on a highly precise micrometer-sized restriction in the channels. The main difference between the two chip types is that a sheet flow is created in combination with a restriction in case of the Focused-Flow Droplet Generator whereas the T-Shaped Droplet Generator solely relies on the shear force at the channel Tee.

a)



b)

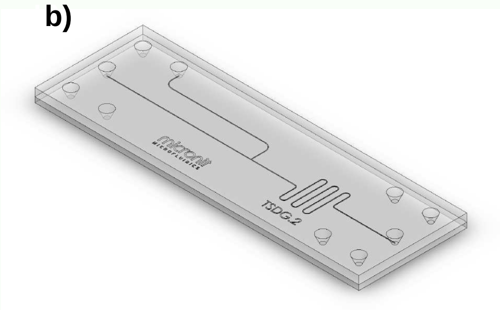
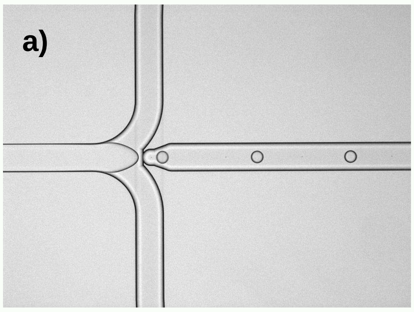


Figure 1: *a) Focused-Flow Droplet Generator chip and b) T-Shaped Droplet Generator chip.*

1.2 Droplet formation

Figure 2 shows images of the formation of hexadecane droplets with a diameter of approximately 40 µm and a volume of 25 pL. Changing the flow rate of the two phases allows the size of the droplets to be increased or reduced. The formation of water droplets inside an organic phase can be accomplished when the channels are coated with a substance having a hydrophobic moiety in order to enhance the wetting by the organic phase.

a)



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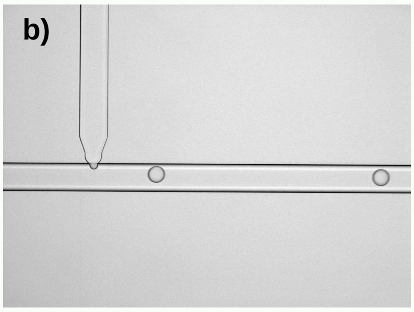

Figure 2: *Hexadecane droplet formation in a) a* FC_FFDG.2 chip and b) a FC_TSDG.2 chip. The continuous phase is deionized water containing 2% (v/v) Tween 20. The flow rates are 0.2 µL/min hexadecane and 5.0 µL/min water.

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2 Introduction

Microfluidic droplet generators are used to create a stream of monodispersed water or oil droplets in an immiscible phase. Applications where droplet based microfluidics are used include [1]:

- Chemical reactions
- Therapeutic agent delivery (e.g. controlled drug release)
- Biomolecule synthesis
- Diagnostic chips
- Drug discovery (e.g. cell culturing)

The advantages of droplet based microfluidics compared to continuous phase microfluidics include:

- Compartimentalization
- Enhanced mixing due to internal recirculation
- Monodisperse particle generation
- Highly parallelized experiments

Microfluidic droplet generators work by combining two or more streams of immiscible fluids and generating a shear force on the discontinuous phase causing it to break up into discrete droplets. The capillary number, *Ca*, is often used to predict droplet behaviour:

$$Ca = \frac{\eta \nu}{\gamma}$$

where η (Pa.s) and ν *(m/s)* are the viscosity respectively the velocity of the continuous phase, and γ(N/m) is the interfacial tension between the two immiscible phases. Above a critical capillary number, which depends on the channel geometry, droplet formation starts.

The surface wettability of the channels is critical to form water-in-oil (W/O) or oil-in-water (O/W) droplets. To prevent sticktion of droplets oil droplets are made in hydrophilic channels (untreated glass) and water droplets in hydrophobic channels (coated glass).

Surfactants are used to alter the channel surface wettability and to prevent coalescence of the droplets.

3 Droplet generator chips

Micronit offers two types of droplet generator chips (see Fig. 1 and Table 1). Both the Focused-Flow Droplet Generator chip (FFDG) and the T-Shaped Droplet Generator chip (TSDG) rely on a highly precise micrometer-sized restriction in the channels. The main difference between the two chip types is that a sheet flow is created ahead of the restriction in case of the Focused-Flow Droplet Generator whereas the T-Shaped Droplet Generator solely relies on the shear force at the channel Tee.

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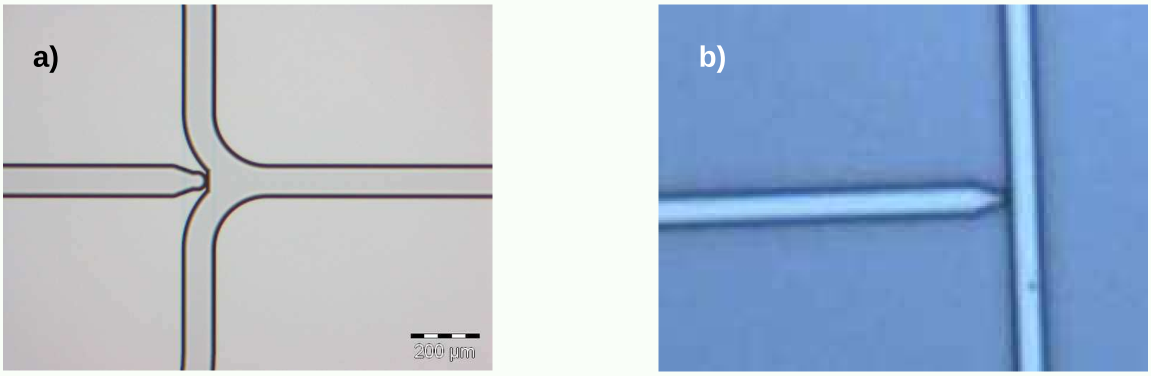

Figure 1: *a) Focused-Flow Droplet Generator chip and b) T-Shaped Droplet Generator chip.*

Table 1: *Micronit standard droplet generator chips*

	Bottom Glass Layer (µm)	Top Glass Layer (µm)	Internal Volume (µl)	Channel Width (µm)	Channel Depth (µm)	Nozzle Size (µm)
FC_TSDG.2	1100	700	0.17	100	20	10
FC_FFDG.2	1100	700	0.18	100	20	10

4 Experimental

Oil-in-water droplets were generated using untreated FC_TSDG.2 and FC_FFDG.2 chips. The chips were inserted into the Fluidic Connect chip holder and connected to two syringe pumps using fused silica capillaries. Two 250 µL glass syringes were filled with hexadecane and filtered deionized water containing 2% (v/v) Tween 20 respectively. The flow rate of the organic phase and water phase was adjusted independently of each other in the range of 0.1 µL/min to 15 µL/min. In order to generate water-in-oil droplets chips with a perfluoro surface coating were used.

5 Results

5.1 Oil-in-water droplets

4.1.1 Focused-Flow Droplet Generator

Table 2 shows images of the formation of HD droplets at varying pumping speeds. In these images the direction of the flow is from right to left. Droplets with a diameter between 29 µm to 65 µm were generated depending on the pumping rate of the two phases. Note that the channel depth is 20 µm so inside the chip the shape of the droplets is that of a flattened sphere with a volume of approximately 13 to 66 pL. The speed at which the droplets form is in the order of 650 droplets per second (e.g. Table 2, 1.0 µL/min HD and 7.5 µL/min water). The table also shows that when the velocity of the water phase becomes much higher than that of the oil phase that droplets tend to be formed in pairs.

The fluid emerging from the chip was collected on a microscope slide demonstrating the monodispersity of the droplets (See Fig. 2). A closer look does show that mixed in with the large droplets there is a small fraction of much smaller droplets which also have a small size distribution.

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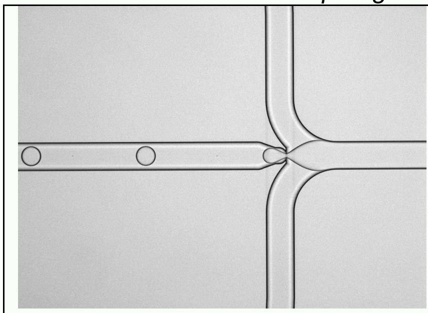
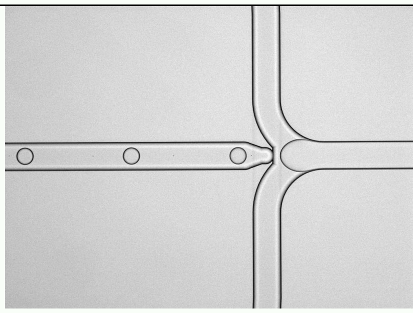
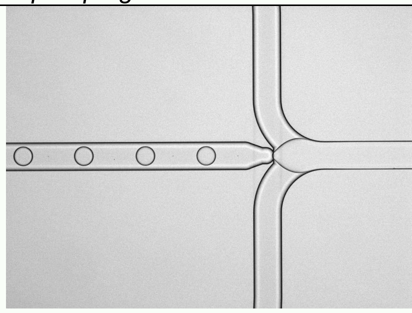
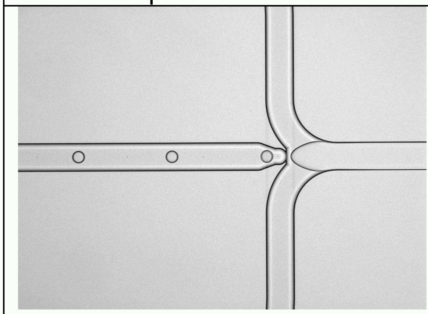
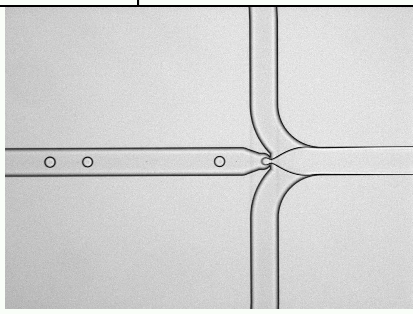
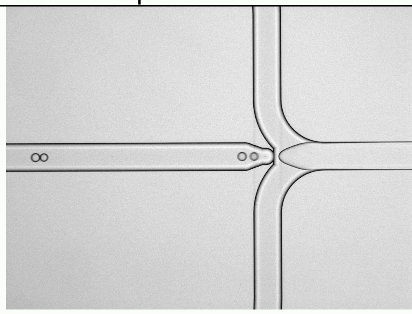
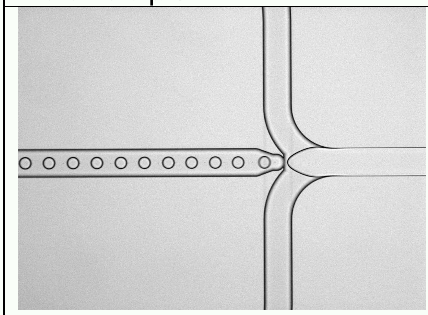
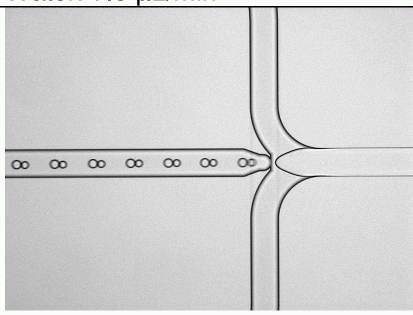
Table 2: *Hexadecane droplet generation at different hexadecane and water pumping velocities.*

 HD: 0.1 µL/min Water: 1.0 µL/min	 HD: 0.1 µL/min Water: 2.0 µL/min	 HD: 0.2 µL/min Water: 2.0 µL/min
 HD: 0.2 µL/min Water: 5.0 µL/min	 HD: 0.2 µL/min Water: 7.5 µL/min	 HD: 0.2 µL/min Water: 10.0 µL/min
 HD: 1.0 µL/min Water: 7.5 µL/min	 HD: 1.0 µL/min Water: 15.0 µL/min	

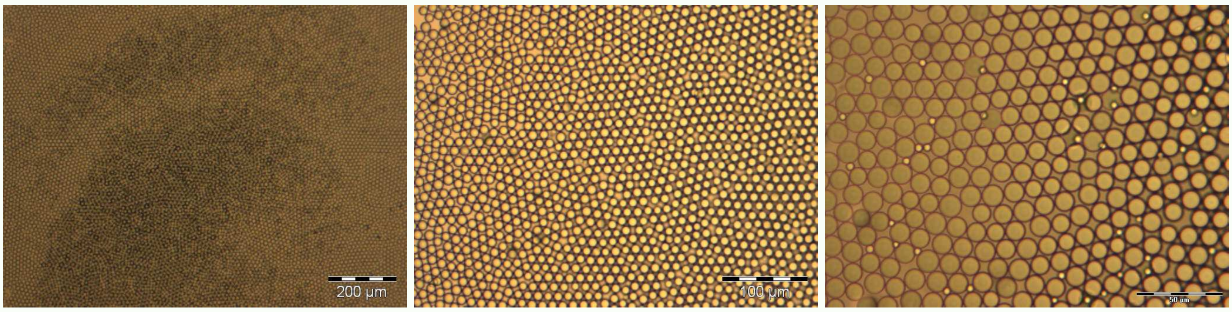
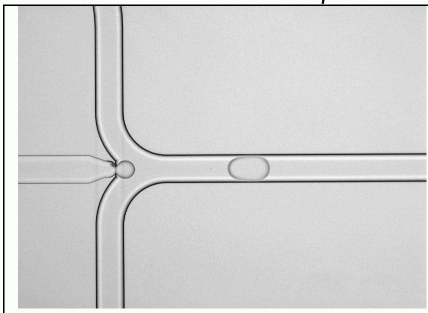
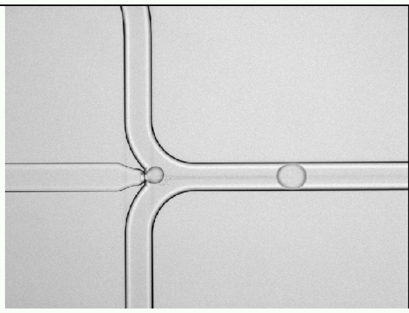
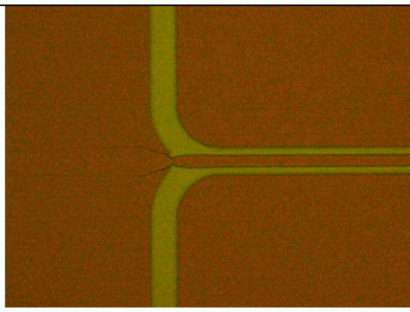


Figure 2: *Droplets collected from the chip at three different magnifications. HD: 1.0 µL/min, water: 7.5 µL/min.*

4.1.2 Focused-Flow Droplet Generator: Reversed direction

When the chip is connected in the reverse direction (fluid flows from left to right in Table 2) the droplets do not shear off readily and it was not possible to generate droplets that were narrower than the channel width (see Table 2). When HD was pumped sufficiently fast an annular flow was obtained which was stable throughout the entire length of the channel without collapsing into a plug flow (see the last image in Table 2).

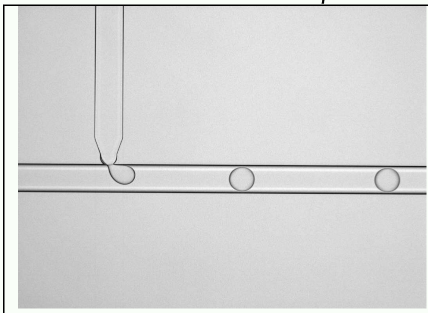
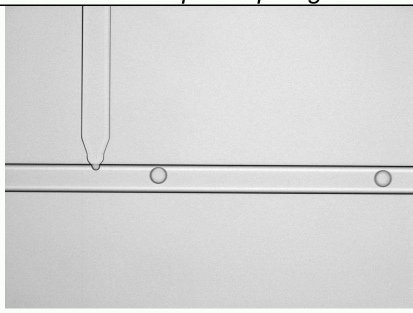
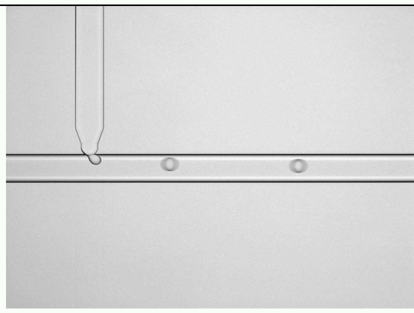
Table 2: *Hexadecane droplet formation in the reversed flow direction*

 *HD: 1.0 µL/min* *Water: 7.5 µL/min*	 *HD: 0.2 µL/min* *Water: 7.5 µL/min*	 *HD: 3.5 µL/min* *Water (with 1 mM fluorescein but without Tween 20): 5.0 µL/min*

4.1.3 T-Shaped Droplet Generator

Images of droplets made using the T-shape droplet generator are shown in Table 3. With a HD rate of 0.2 µL/min and a water rate of 7.5 or 10.0 µL/min no stable droplet formation was obtained, although this may also be a result of being too close to the lower operating limit of the syringe pump used. Overall the performance of T-shaped droplet generator is similar to the focused flow droplet generator, with a droplet size and generation rate that is comparable. A difference is that in contrast to the focused flow droplet generator there does not appear to be a regime where the T-shape droplet generator produces droplets in pairs (e.g. compare 1.0 µL/min HD and 15.0 µL/min water in table 1 and 3), which could be a reason to use this design.

Table 3: *Hexadecane droplet formation in the T-shape droplet generator*

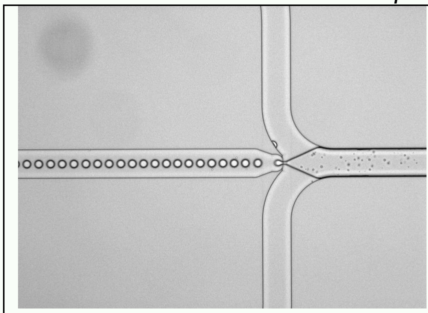
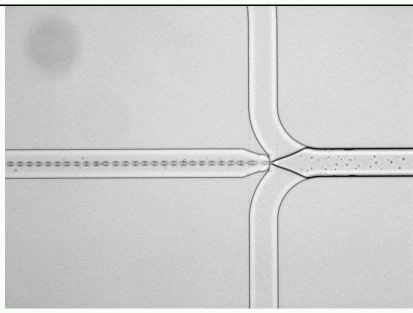
 HD: 0.2 µL/min Water: 2.0 µL/min	 HD: 0.2 µL/min Water: 5.0 µL/min	 HD: 1.0 µL/min Water: 15.0 µL/min

5.2 Formation of water-in-oil droplets with perfluoro coated droplet generator chips

4.2.1 Focused-Flow Droplet Generator

Using the focused-flow generator chip, the water droplets were smaller and generated at a higher frequency then when generating O/W droplets using the same pumping speeds for the continuous and dispersed phase (see Table 4). At low pumping speeds of the continuous phase the droplet formation was unstable which was not the case when generating O/W droplets. Overall the operating range was much narrower, which is probably caused by the wetting characteristics of the coated surface which need to be tuned further to improve the wetting by hexadecane and reduce the wetting by water.

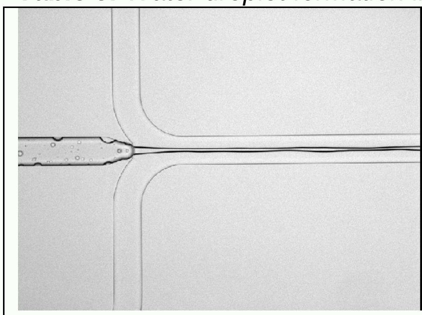
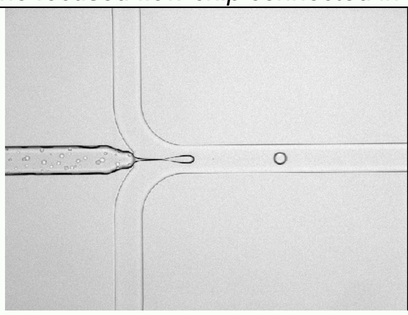
Table 4: *Formation of water droplets at different hexadecane and water pumping velocities*

 HD: 10.0 µL/min Water: 1.0 µL/min	 HD: 15.0 µL/min Water: 1.0 µL/min	**Unstable** HD: 5.0 µL/min Water: 1.0 µL/min

4.2.2 Focused-Flow Droplet Generator: Reversed direction

In the reverse direction smaller water droplets could be generated using the coated chip than oil droplets in the uncoated chip (see Table 5).

Table 5: *Water droplet formation in the focused flow chip connected in the reversed flow direction*

 HD: 5.0 µL/min Water: 1.0 µL/min	 HD: 10.0 µL/min Water: 1.0 µL/min

6 Conclusions

With the FC_FFDG.2 and FC_TSDG.2 droplet generator chips monodisperse droplets can be generated with a diameter in the range of approximately 29 µm to 65 µm inside the chip. The focused flow droplet generator appeared to be slightly more stable over a larger range of flow rates. On the other hand the T-shaped droplet generator produced droplets at constant intervals where the focused flow droplet produced droplets in pairs at a high continuous phase flow rate.

7 References

1 S-Y. Teh, R. Lin, L-H. Hung and A.P. Lee; “Droplet microfluidics”; Lab Chip 2009, **8**, 198-220

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