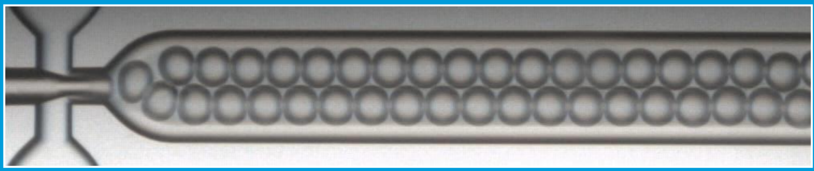
Generation of Water Droplets in a Hexadecane Carrier Stream

Dolomite's Droplet Generation System - Large Droplets



Summary

Microfluidics is an ideal tool for droplet generation. Droplets can be used for a wide range of applications, including encapsulation of reagents or other ingredients, forming emulsions of precise droplet size and concentration, forming foams and gas bubbles, etc.

When compared with traditional batch methods, microfluidics has many advantages, as illustrated in the table below:

Dolomite Microfluidic Method	Batch Method
Monodisperse (CV <5%)	Polydisperse (CV >>20%)
Scale to kg/day with no waste	~50% waste
Consistent from run to run	Poor batch to batch consistency
Uniform ingredient distribution	Uneven ingredient distribution
Precise droplet size control	Poor size control
Wide range of droplet size available	Limited size range without filtering

Chart showing flow regimes at varied pressures.

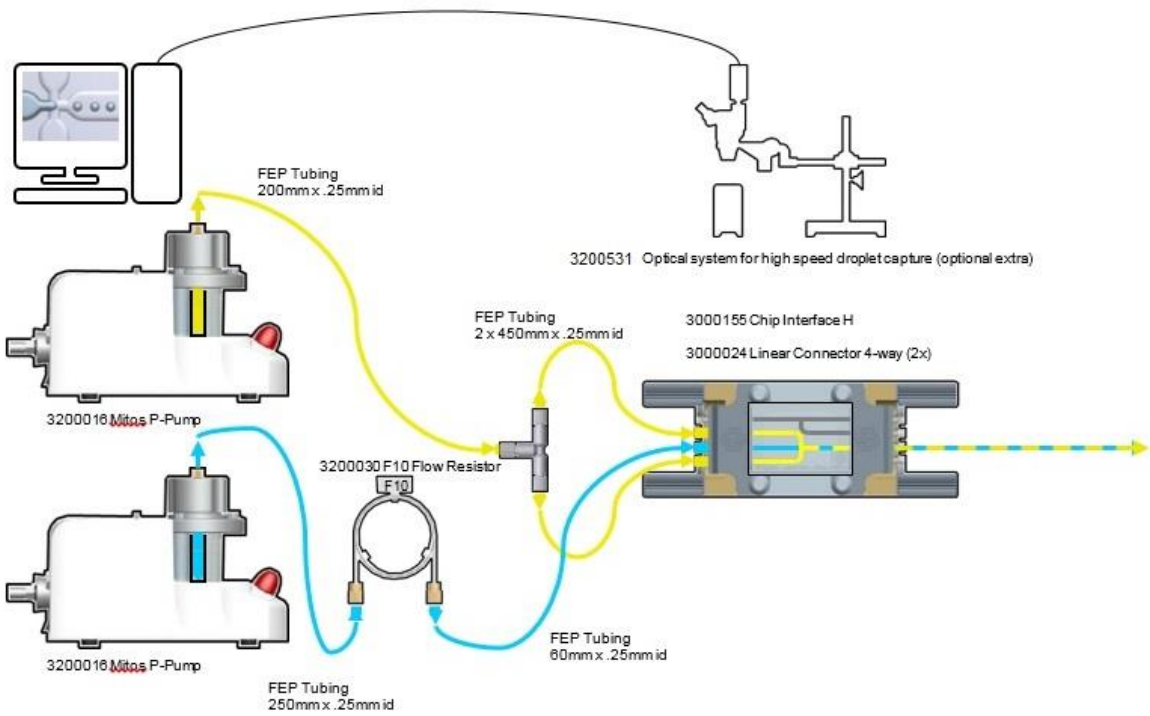
The formation of monodisperse droplets of oil-in-water or water-in-oil has a range of uses in science and industry:

Droplet Application Example	Requirement for Monodispersity
Emulsion production in food or cosmetics	Consistent texture and performance of sample
Droplets as mini chemical reactors	Known chemical make-up of droplets to achieve a reaction
Drug delivery	Controlled dispersion of active ingredients
Performing biochemical assays or screens	Ability to keep conditions inside droplet constant and measure the effect of a single parameter

This application note describes an experimental set-up for the generation of water droplets in an oil carrier stream with the Droplet Junction Chip. By controlling the pressure of the oil and water input reservoir (using the Mitos P-Pump), different flow regimes and droplet sizes were observed.

Experimental Setup

In the experimental set-up shown below the two Mitos P-Pumps (Part No. 3200016) deliver oil and water streams to the Droplet Junction Chip (100 µm etch depth), hydrophobic (Part No. 3000301). This chip is mounted on the Chip H Interface (Part No. 3000155) and fluidically sealed using 2 Linear Connector 4-way (Part No. 3000024). The connection between the pumps and the chip are realized by means of FEP tubing of OD 1.6 mm and ID 0.25 mm (Part No. 3200063).



Schematic of the Dolomite's Large Droplet Generation System.

By estimating the flow resistance and recording the two pressures, flow rates for the two liquids and pressure at the droplet junction can be calculated using the correlation reported in Appendix A. The Dolomite Flow Control Centre Advanced software enables accurate and simultaneous control of pressure via a PC.

Optical system for high speed video (Part No. 3200531) was used to measure droplet generation rates and droplet size.

The droplet liquid was water and the carrier liquid was hexadecane with 1% (v/v) Span80. Span80 is a surfactant used to stabilise the droplets and prevent downstream coalescence.

Dolomite Large Droplet Generation System.

This application note describes the generation of water-in-oil droplets using the X-junction geometry (100 µm etch depth). A T-junction geometry (100 µm etch depth) is also etched on the same glass chip to be able to create water-in-oil droplets using only one stream of water and oil. The X-junction geometry works generally better than the T-junction as it offers higher control over the droplet size.

Details of the Droplet Junction Chip mounted on the H interface. The glass chip contains both the X and T junctions.

Results

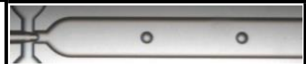
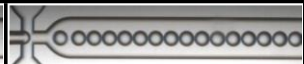
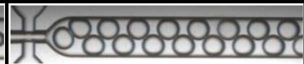
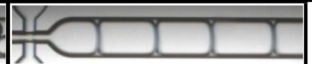
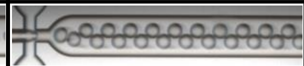
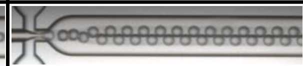
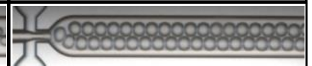
Oil Pressure /mbar	Water Pressure /mbar: 30	100	300	1000	3000	6000
30	 Regime: Dripping, Monodispersed Rate: 11 dps Diameter: 90.8µm	 Regime: Dripping, Monodispersed Rate: 23 dps Diameter: 112.0µm	 Regime: Dripping, Monodispersed Rate: 32 dps Diameter: 158.5µm	 Regime: Dripping, Chaotic Rate: Diameter:		CHAOTIC
100	 Regime: Dripping, Monodispersed Rate: 56 dps Diameter: 46.5µm	 Regime: Dripping, Monodispersed Rate: 70 dps Diameter: 73.9µm	 Regime: Dripping, Monodispersed Rate: 140 dps Diameter: 86.6µm	 Regime: Dripping, Monodispersed Rate: 250 dps Diameter: 109.9µm	 Regime: Dripping, Chaotic Rate: Diameter:	
300		 Regime: Dripping, Monodispersed Rate: 234 dps Diameter: 44.4µm	 Regime: Dripping, Monodispersed Rate: 404 dps Diameter: 59.2µm	 Regime: Dripping, Monodispersed Rate: 752.6 Diameter: 73.9µm	 Regime: Dripping, Monodispersed Rate: 1549 dps Diameter: 84.5µm	 Regime: Dripping, Monodispersed Rate: 1654 dps Diameter: 105.6µm
1000			 Regime: Dripping, Monodispersed Rate: 2787 dps Diameter: 27.5µm	 Regime: Dripping, Monodispersed Rate: 4305 dps Diameter: 40.6µm	 Regime: Dripping, Monodispersed Rate: 7924 dps Diameter: 48.6µm	 Regime: Jetting, Monodispersed Rate: 1362 dps Diameter: 114.1µm
3000	BACKFLOW			 Regime: Jetting, Monodispersed Rate: 42403 dps Diameter: 16.9µm	 Regime: Jetting, Monodispersed Rate: 5040 dps Diameter: 54.9µm	 Regime: Jetting, No Droplets Rate: Diameter:
6000					 Regime: Jetting, No Droplets Rate: Diameter:	 Regime: Jetting, No Droplets Rate: Diameter:

Chart showing flow regimes at varied pressures.

The images captured during the experiment show the flow regimes at various pressure combinations. Four different flow regimes were observed:

- **Dripping regime** – This occurs at lower flow rates and results in monodisperse droplet formation. Droplets range between about 20 µm and > 100 µm. Droplets larger than the chip junction size (100 µm) are squashed cylinder or slugs. The calculation of their volumes is presented below.
- **Jetting regime** – This occurs at higher flow rates and can result in monodispersed droplets but can also give polydisperse droplets. At very high flow rates annular flow can occur with no droplet formation.
- **Chaotic** – This occurs when the water flow rate is significantly higher than the oil flow rate. Droplet size is generally polydisperse.
- **Backflow** – This is characterised by the oil stream flowing back into the water feed channel. This occurs when the backpressure generated in the output channel and output pipe is greater than the pressure set on the water Mitos P-Pump. To avoid backflow the resistance of the flow resistor on the water input stream should be increased.

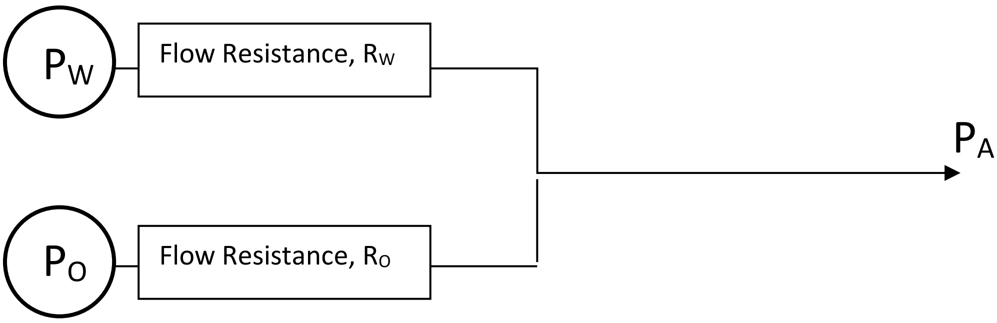
Conclusion

The flow regime chart illustrates that there is a region where monodisperse droplet generation occurs. The pressure ratio can be used to adjust droplet size. When the difference in the flow rates of the two phases is very large, the flow may become chaotic with no droplets formed. With increased pressures droplets can be generated at over 10,000 droplets per second in a range between about 20 µm and > 100 µm.
The Dolomite's Large Droplet Generation System presented in this application note is available with different junction sizes and surface coatings (hydrophilic, hydrophobic and fluorophilic) for the generation of water-in-oil droplets and oil-in-water droplets. Details in the Appendix below.

Appendix A: Flow Rate and Droplet Volume Calculation

Flow Rate Calculation

The fluidic layout can normally be represented schematically as shown in the diagram below where W is the water droplet stream and O is the oil carrier fluid. This assumes that the flow resistance after the droplet junction, R_J, is low relative to the flow resistance of the two input streams R_W and R_O.



The flow rate in each feed stream can be estimated using the following two equations:

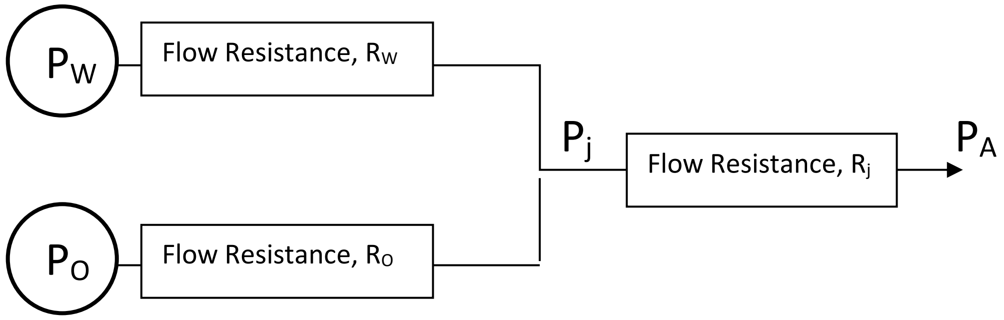
$$Q_W = \frac{P_W}{R_W \times \mu_W}, \qquad Q_O = \frac{P_O}{R_O \times \mu_O}$$

Q = Flow rate
P = Pressure in P-Pump
μ = viscosity
R = flow resistance

The Microfluidic Calculator on www.dolomite-microfluidics.com can be used to estimate flow rates using the equation shown above.

If R_j is high relative to R_x and R_y then it is necessary to first calculate the pressure at the droplet junction to get an accurate estimate of all the flow rates in the system.

The schematic below shows R_J and the equation can be used to estimate the pressure at the junction, P_J. The equation assumes that the viscosity of the output stream is equal to the viscosity of the carrier fluid. This is generally a good approximation if the carrier flow rate is higher than the droplet flow rate.



$$P_J = \frac{P_W.W + P_O.O}{J + W + O}$$

Where:

$$W = \frac{1}{R_W \times \mu_W}, \qquad O = \frac{1}{R_O \times \mu_O}, \qquad J = \frac{1}{R_J \times \mu_O}$$

R_W = flow resistance of the water input channel

R_O = flow resistance of the oil input channel

R_J = flow resistance of the channel after the junction

μ_W = viscosity of water

μ_O = viscosity of oil

P_J = pressure at junction

P_W = Mitos P-Pump pressure on water

P_O = Mitos P-Pump pressure on oil

The flow rates can then be calculated as follows:

$$Q_W = (P_W - P_J).W, \qquad Q_O = (P_O - P_J).O$$

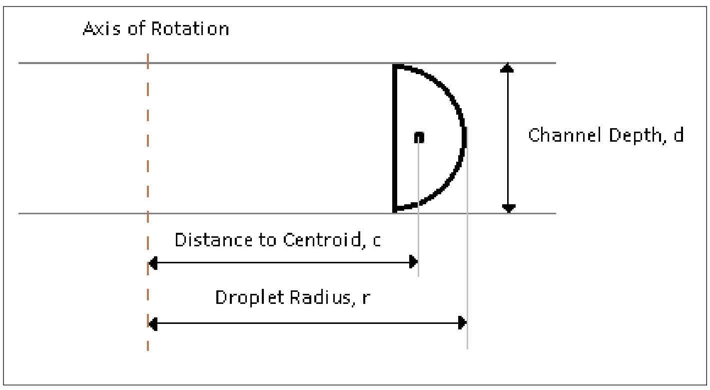
These equations are useful for predicting backflow scenarios for a Mitos P-Pump set-up.

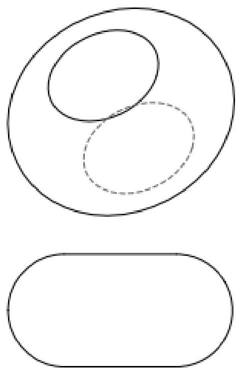
Droplet Volume Calculation

Droplet volume is normally calculated assuming a spherical droplet shape. If the diameter of the droplet observed in a microchannel is greater than the channel depth (100µm in this instance) then the droplet shape will be a squashed cylinder, as shown below. The equation for calculating the volume of this cylinder is shown below.

Equations Used

For Spherical Droplet	**Droplet D < Channel Depth**
Volume of Droplet	$V = \frac{4}{3}\pi r^3$
For Squashed Cylinder	**Droplet D > Channel Depth**
Volume of Cylinder	$V_c = \pi d \left(r - \frac{d}{2}\right)^2$
Distance to Centroid	$c = r - \frac{d}{2} + \frac{4}{3}\frac{\left(\frac{d}{2}\right)}{\pi}$
Area of Semicircle	$A_s = \pi \frac{d^2}{8}$
Volume of Semicircular Ring	$V_s = 2\pi A_s c$
Total Droplet Volume	$V_t = V_c + V_s$





Side View of Droplet

Appendix B: System Component List

Part No.	Part Description	#
3200675	Dolomite's Droplet Generation System - Large Droplets The system includes:	-
	Mitos P-Pumps	2
	Sensor Displays *	2
	Flow Rate Sensors *	3
	High-Speed Digital Microscope	1
	Valves, Chip Interfaces, Fittings and Tubing	-
	Mitos Compressor 6bar	1
3000158	Droplet Junction Chip (100µm etch depth)	1
3000436	Droplet Junction Chip (190µm etch depth)	1
3000301	Droplet Junction Chip (100µm etch depth), hydrophobic	1
3000437	Droplet Junction Chip (190µm etch depth), hydrophobic	1
3200506	Droplet Junction Chip (190µm etch depth), fluorophilic	1
3200512	Droplet Junction Chip (100µm etch depth), fluorophilic	1
	Installation and Training	-

* The Flow Rate Sensors are compatible with the Mitos P-Pumps. The Mitos P-Pump communicates directly with the Flow Sensors to adjust the pressure and achieve the desired flow rates. The flow rates can be easily set using the Flow Control Centre Software working in flow mode rather than pressure mode (as described in the application note).

Each Sensor Display can be used interchangeably with the Flow Rate Sensors. The sensors simply attach with a push-click action. In this specific application note, the Flow Rate Sensors 1-50 µl/min (Part No. 3200098) can be mounted on the P-pump which controls the water stream and Flow Rate Sensors 30-1000 µl/min (Part No. 3200097) can be mounted on the oil stream.