# Formation of Droplets and Bubbles in a Microfluidic T-junction – Scaling and Mechanism of Break-Up

## Supplementary Information

Piotr Garstecki[1,2]*, Michael J. Fuerstman[1], Howard A. Stone[3]
and George M. Whitesides[1]*

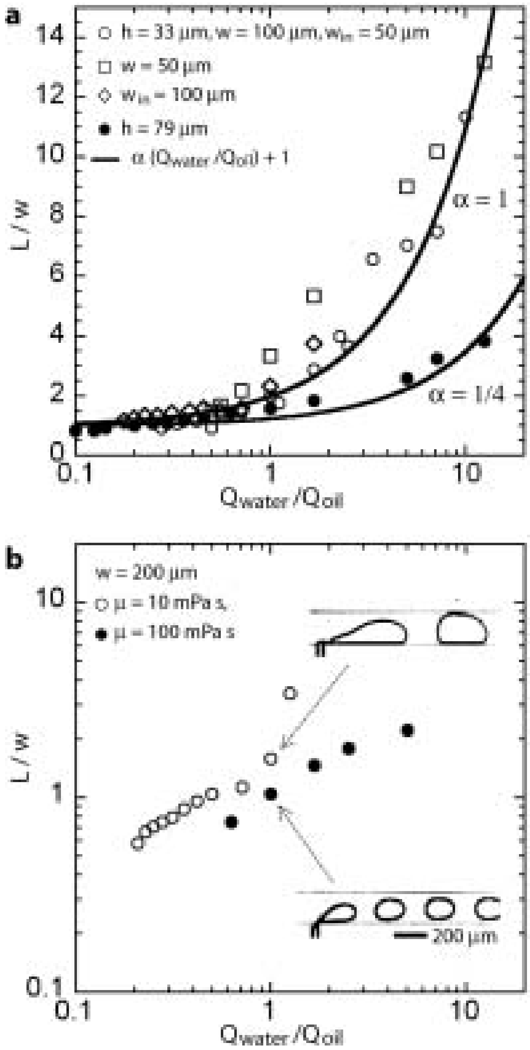
[1]*Department of Chemistry and Chemical Biology, Harvard University*
*12 Oxford St., Cambridge, MA 02138, U.S.A.*
[2] *Institute of Physical Chemistry, Polish Academy of Sciences*
*Kasprzaka 44/52, 01-224 Warsaw, Poland*
[3] *Division of Engineering and Applied Sciences, Harvard University*
*29 Oxford St., Cambridge, MA 02138, USA*

* electronic address: (PG) garst@ichf.edu.pl, (GMW) gwhitesides@gmwgroup.harvard.edu

**Liquid-Liquid system.** In Supplementary Figure 1a we plot the lengths of droplets measured for four different geometries (for dimensions please see Table 1) and the model predicts the size well for all of the series. Again, without employing a detailed fitting procedure, we assume $\alpha = 1$ in all cases other than the series measured in a device with $h$ = 79 μm, for which we obtain a reasonably good fit when $\alpha = 1/4$. The lower value of $\alpha$ in this case can be attributed to the aspect ratio of the height of the channel to the width of the inlet for the discontinuous phase. Since $h/w_{in} \approx 3/2$, and the radial curvature is not bound by the height of the channel, the neck assumes a circular cross-section almost immediately after it is formed and collapses faster than in geometries in which $h < w_{in}$, consequently leading to smaller droplets.

We note that when the width $w$ of the main channel is much greater than the width $w_{in}$ of the inlet channel, we observe the effects of the shear stress exerted on the liquid-liquid interface. In Supplementary Figure 1b we show two series of data taken in a channel with $w$ = 200 μm ($w/w_{in}$ = 4). The process of break-up in this geometry cannot be described by the squeezing model because the droplets do not fill the cross-section of the main channel before they break off from the inlet. Under these circumstances the viscosity of the continuous fluid changes the observed lengths of the droplets in a systematic way (Supplementary Figure 1b). The transition from squeezing ($\varepsilon/w << 1$) to shearing ($\varepsilon \sim w$) may be estimated simply: if the typical length-scale $l^*$ at which the shear stress is exactly balanced by the Laplace pressure $l^* \approx \gamma w / \mu u$ is greater than the width $w$ of the outlet channel, then the emerging drop does not yield to shear exerted by the continuous fluid and effectively blocks the channel. Under these circumstances the squeezing mechanism is expected to describe the break-up. When $l^* / w < 1$, shear stress becomes sufficiently important to affect the sizes of the droplets produced. In practice, however, we observe that the ratio of the width of the inlet channel to the width of the main channel is a very important parameter in this transition. For the same capillary numbers we observe that when $w_{in} / w \geq 1/2$, the droplets break in the 'squeezing' mode (the tip of the immiscible thread blocks the whole cross-section of the main channel), while for $w_{in} / w < 1/2$ we observe that the shear stress exerted on the immiscible tip distorts the drop significantly and the squeezing model and the scaling proposed in this article no longer apply. Detailed analysis of the deformation of a droplet adhering to a wall and subject to simple shear flow – as a function of the ratio of the size of the droplet to the area of attachment, and various other parameters – can be found elsewhere[1-3].

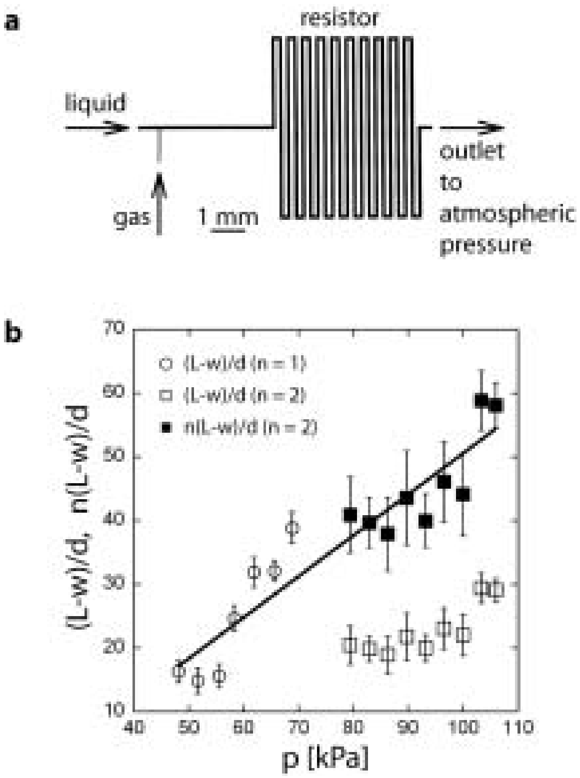
**Supplementary Figure 1**. a) Dimensionless length of the droplet ($L/w$) as a function of the ratio of rates of flow ($Q_{water}/Q_{oil}$) for different geometries. The lengths obtained for the reference geometry $h$ = 33 μm, $w$ = 100 μm, $w_{in}$ = 50 μm are denoted with (○). In the next three series we changed the following geometrical parameters: the width of the main channel $w$ = 50 μm (□), the width of the inlet channel for the discontinuous fluid $w_{in}$ = 100 μm (◇), and height of the channels $h$ = 79 μm (●). For all the series we kept the rate of flow of the discontinuous phase constant $Q_{water}$ = 0.14 μL/s. The solid lines denotes the fits for $\alpha = 1$ and $\alpha = ¼$. b) The same plot for a T-junction geometry ($h$ = 33 μm, $w_{in}$ = 50 μm) with the widest outlet channel that we tested in our experiments ($w$ = 200 μm), for $Q_{water}$ = 0.14 μL/s, and for two different viscosities of the continuous fluid: μ = 10 mPa s (○), and μ = 100 mPa s (●). In this system the shear stress exerted on the forming droplet has significant influence on its shape and on the break-up process (see insets, both obtained for $Q_{oil}$ = 0.14 μL/s).




**Gas-Liquid system.** In order to check that the length of the bubbles produced in the T-junction is inversely proportional to the viscous resistance to flow in the outlet channel, we changed the length $L_{ch}$ of this channel by incorporating ‘resistors’ – 10 cm long sections of the outlet channel. According to the squeezing model, $(L - w) / d = Q_{gas} / Q_{liquid} = p / Q_{liquid} R \propto p / L_{ch}$ (because $R \propto \mu$) and hence $[(L - w) / d]\ L_{ch} \propto p$.

Experiments with networks containing one ($n = 1$) and two ($n = 2$) resistors confirm this scaling (see supplemental Figure 2) – a two fold increase of the resistance of the outlet channel caused a twofold decrease of the size of the bubbles.

**Supplementary Figure 2**. a) A micrograph of the microfluidic T-junction device with one fluidic ‘resistor’ – a 10-cm-long section of channel added to the device. In the experiments with two fluidic resistors, the second resistor of the same geometry was positioned downstream of the second one. We vented the end of the outlet channel directly to the atmosphere. In this picture we filled the channels with black dye to visualize them. b) Scaling of the length of the bubbles with the length of the outlet channel (with one ($n = 1$) or two ($n = 2$) resistors). The solid line gives a linear fit of the combined series $(L\text{-}w)/d$ for ($n = 1$) and $2(L\text{-}w)/d$ for ($n = 2$). The width of the channel is $w = 100$ µm and the fitting parameter $d = 50$ µm.




## References


[1] A. D. Schleizer, R. T. Bonnecaze, *J. Fluid Mech.* 1998, **383**, 29-54.
[2] X. F. Li, C. Pozrikidis, *J. Fluid Mech.* 1996, **307**, 167-190.
[3] S. Yon, C. Pozrikidis, *Phys. Fluids* 1999, **11**, 1297-1308.