Electronic Supplementary Material (ESI) for Lab on a Chip.

Supporting information of "Robust scalable high throughput production of monodisperse drops"

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Influence of the nozzle geometry

To test if we can increase the maximum throughput of an individual nozzle by increasing the opening angle of the reservoir, α, we fabricate a device with α = 35° and a nozzle length l = 330 μm, resulting in $\frac{w}{h}$ = 24. However, drops produced in these devices have a significantly broader size distribution than those produced in devices with smaller opening angles, as shown in Fig. S1.

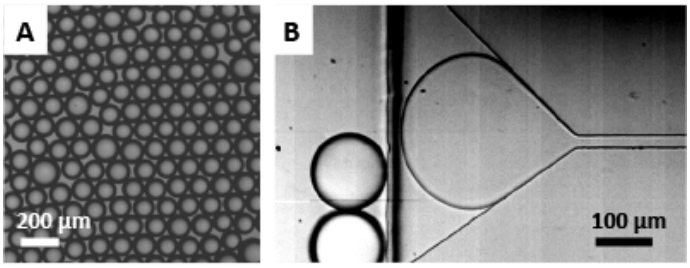

Figure S1: Optical micrographs of (a) drops produced in a reservoir with an opening angle, α = 35° and a length, l = 330 μm and (b) the drop formation in this reservoir.

Influence of device height on maximum throughput

If the injection rate of the inner phase is too high, drop production transitions from the dripping into the jetting regime. To quantify the flow rate at which this transition occurs as a function of the nozzle height, h, we employ a device containing 500 nozzles with h varying between 10 μm and 60 μm. We produce drops from an aqueous phase containing 10 wt% PEG 6kDa, which has a viscosity of 3 mPas. The maximum flow rate of the inner phase, at which the device can be operated in the dripping regime scales with $h^{\frac{3}{2}}$, as derived in the main paper and shown in Fig. S2.

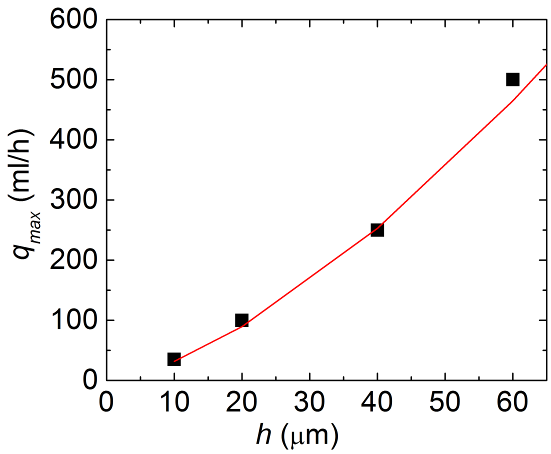

Figure S2: Influence of the nozzle height, h, on the maximum flow rate of the inner phase at which a device with 500 nozzles can be operated in the dripping regime, q_{max}.

Calculations of the tongue shape

The fluid adopts a tongue shape inside the reservoir; its radius in the horizontal plane $R(x_T)$ can be expressed as a function of the device geometry and the fluid contact angle with the walls α; here x_T is the coordinate of the tip of the tongue starting where the cross-section of the nozzle perpendicular to the fluid flow begins to increase and measured on a horizontal axis going through the middle of the drop maker.

Using Figure 1 of the main paper, we can relate $R(x_T)$ to the device geometry and contact angle:

$$\cos(\alpha - \theta) = \frac{b + x_0 \tan\theta}{R(x_T)} \qquad \text{and} \qquad R(x_T)\sin(\alpha - \theta) + (x_T - x_0) = R(x_T)$$

Solving for the radius we obtain:

$$R(x_T) = \frac{b + x_T \tan\theta}{\cos(\alpha - \theta) + \tan\theta(1 - \sin(\alpha - \theta))} \tag{1}$$

Once the fluid passes the step and enters the tall collection channel, a drop precursor forms. It is more convenient to parametrize the problem with a, the semi- major axis of the ellipse than x_T. They are related by $x_T = L + R(x_T) - \sqrt{R(x_T)^2 - a^2}$. Inserting this expression in (1) and solving for $R(x_T)$, we get:

$$R(a) = \frac{A(1 - v) - v\sqrt{A^2 + a^2(2v - 1)}}{1 - 2v}$$

with

$$A = \frac{b + \tan\theta\, L}{\cos(\alpha - \theta) + \tan\theta(1 - \sin(\alpha - \theta))} \quad \text{and} \quad v$$

$$= \frac{\tan\theta}{\cos(\alpha - \theta) + \tan\theta(1 - \sin(\alpha - \theta))}$$

The radius, r, of the drop precursor, which is equal to the short axis of the ellipsoid, is obtained by imposing the constant mean curvature condition. The mean curvature of the fluid outside the nozzle is $1/2r$ while inside we have two contributing terms: the curvature in the horizontal plane $1/R(a)$ and the curvature in the vertical plane $2\cos\alpha/h$, where h is the height of the nozzle.

$$\frac{1}{r} = \frac{2\cos\ \alpha}{h} + \frac{1}{R(a)}$$

For very small drops production, the first term dominates and so $r \approx h/2cos\alpha$.

At breakup, the drop precursor has the shape of an ellipsoid of radius r and length $9r$, implying a linear scaling for the droplet radius with h.

Movie S1: Formation of aqueous drops in a 330 μm long, 20 μm tall reservoir whose opening angle, α, is 19°; therefore, the ratio of the width at the step to the height is $\frac{w}{h}$ = 12.4 and $\frac{V_{res}}{V_{drop}}$ = 7.3. The aqueous phase contains 20 wt% PEG 6 kDa to increase the viscosity and polystyrene beads to visualize the fluid flow. We used fluorinated oil containing fluorinated surfactants as an outer phase. The movie is 100 times slowed down.

Movie S2: Formation of aqueous drops in a 330 μm long, 20 μm tall reservoir whose opening angle, α, is 19°; therefore, the ratio of the width at the step to the height is $\frac{w}{h}$ = 12.4 and $\frac{V_{res}}{V_{drop}}$ = 7.3. The outer phase contains very small thioglycerol drops that were added to visualize its flow. The movie is 100 times slowed down.

Movie S3: Formation of aqueous drop in a 200 μm long, 20 μm tall reservoir whose opening angle is 90°. The flow rate of the inner phase is 5.5 mL/h, that of the outer phase is 20 mL/h. Drops break up at the initial step of the reservoir, which is its entrance. The movie is 10 times slowed down.

Movie S4: Formation of aqueous drop in a 200 μm long, 20 μm tall reservoir whose opening angle is 90°. The flow rate of the inner phase is 7 mL/h, that of the outer phase is 20 mL/h. Drops break up after they passed the step, at the final opening of the reservoir. The movie is 10 times slowed down.