Reducing the shell thickness of double emulsions using microfluidics

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Abstract Double emulsion drops are well-suited templates to produce capsules whose dimensions can be conveniently tuned by adjusting those of the drops. To closely control the release kinetics of encapsulants, the composition and thickness of the capsule shell must be precisely tuned; this is greatly facilitated if the shell is homogeneous in its composition and thickness. However, the densities of the two drops that form the double emulsion are often different, resulting in an offset of the two drop centers and therefore in an inhomogeneous shell thickness. This difficulty can be overcome if the shell is made very thin. Unfortunately, a controlled fabrication of double emulsions with thin shells is difficult. In this paper, we present a microfluidic squeezing device that removes up to 93 vol% of the oil from the shell of water–oil–water double emulsions. This is achieved by strongly deforming drops; this deformation increases their interfacial energy to sufficiently high values to make splitting of double emulsions into double emulsions with a much thinner shell and a single emulsion oil drop energetically favorable. Therefore, we can reduce the shell thickness of the double emulsion down to 330 nm. Because this method does not rely on solvent evaporation, any type of oil can be removed. Therefore, it constitutes a new way to produce double emulsions with very thin shells that can be converted into thin-shell capsules made of a broad range of materials.

Keywords Microfluidics · Double emulsions · Shell thickness · Liquid removal

1 Introduction

Capsules are often used to protect active ingredients from degradation or chemical reactions, for example in food (Downham and Collins 2000; Chen et al. 2006; Hatcher et al. 2008), cosmetics (Miyazawa et al. 2000; Jacquemond et al. 2009), pharmacy (Bibby et al. 2000; Mora-Huertas et al. 2010), or agriculture (Gorla et al. 2015). A capsule can be made from a double emulsion drop, which is a drop contained in a second, larger drop made of an immiscible liquid that is dispersed in a third fluid (Datta et al. 2012). If such drops are converted into capsules, their shell thickness varies, hampering good control over the release kinetics of encapsulants (Datta et al. 2012). This difficulty can be overcome if the shell is made very thin such that the offset of the two centers is minimal.
Reduction in the shell thickness brings an additional benefit: It makes double emulsions more stable against rupture. Rupture of double emulsion drops is typically caused by the coalescence of the innermost aqueous drop with the continuous aqueous phase. For this coalescence to occur, the innermost drop must move toward one of the interfaces between the outer oil drop and the continuous aqueous phase; this movement requires flow of fluid contained in the double emulsion shell (Kim et al. 2011). The hydrodynamic resistance that impedes this fluid flow increases with decreasing shell thickness (Tanyeri et al. 2011), and if the shell is sufficiently thin, the hydrodynamic resistance becomes so high that only minimal fluid flow occurs. As a result, double emulsions with thin shells have a lower propensity to coalesce. Unfortunately, it is very difficult to make double emulsion drops with shell thicknesses below 5 µm using microfluidics. It can be achieved by employing special glass capillary devices that are designed to make double emulsion drops with thin shells (Kim et al. 2011; Lee et al. 2014; Chaurasia et al. 2015). However, the fabrication of these devices is difficult as different tapered glass capillaries must be manually precisely aligned. To overcome this difficulty, microfluidic devices that rely on the same assembly principle but can be fabricated using soft lithography have been developed; their fabrication requires only minimal alignment which facilitates their production (Arriaga et al. 2015). However, these devices can only make double emulsions with shell thicknesses down to 2.5 µm. This thickness can be reduced if their shells contain volatile oils that have some solubility in the outer phase, such that they slowly dissolve and evaporate from the liquid–air interface (Hayward et al. 2006; Arriaga et al. 2014). However, there are only very few solvent mixtures that fulfill all requirements such that they can be removed through evaporation, and these usually contain toxic solvents such as chloroform or toluene, which prevent most biomedical applications (Shum et al. 2008; Thiele et al. 2014). Alternatively, up to 30 vol% of the solvent can be removed from the shell by pushing double emulsions through constrictions (Arriaga et al. 2015; Deshpande et al. 2015). This method does not impose any requirements on the solvent choice, thereby also allowing removal of biocompatible solvents that have no solubility in the aqueous phase whatsoever. However, the amount of oil that can be removed is very limited. Hence, techniques that enable efficient and controlled removal of a wide range of solvents from double emulsion shells remain to be established. Such techniques would facilitate the production of double emulsion drops with thin shells, thereby broadening their use as templates to make thin-shell capsules composed of a wide variety of materials.

In this paper, we introduce a microfluidic squeezing device that enables removal of up to 93 vol% of the oil contained in shells of water–oil–water double emulsion drops. This is achieved by strongly deforming double emulsion drops such that their interfacial energy becomes so high that it is thermodynamically favorable to pinch off the leading end of the drop, which is made solely of oil. Therefore, the double emulsion drop is split into a double emulsion drop with a much thinner shell and a single emulsion drop. The shell thickness of the resulting double emulsion drop can be conveniently controlled with the constriction geometry or the fluid flow rates. This technique constitutes a facile route to controllably reduce the thickness of shells of double emulsion drops after they have been formed without changing the composition of either the shell or the surrounding media.

2 Experimental

We fabricate the microfluidic squeezing device from poly(dimethyl siloxane) (PDMS) using soft lithography (Xia and Whitesides 1998; Mcdonald et al. 2000). It consists of one inlet that leads into a 100-µm-wide channel which is confined on a length of 190 µm to form a constriction whose width varies between 20 and 40 µm, before it opens up again to 100 µm. The drops exit the device through a single outlet, as schematically shown in Fig. 1.

We form water–oil–water double emulsion drops with shell thicknesses below 10 µm using PDMS-based microfluidic devices (Arriaga et al. 2015). These drops...
are composed of an aqueous core containing 20 wt% poly(ethylene glycol) (PEG, $M_w = 6$ kDa), which is added to increase the viscosity of the inner phase, thereby facilitating the assembly of double emulsion drops. The middle phase consists of fluorinated oil (HFE-7500), containing 3 vol% fluorinated surfactants (Holtze et al. 2008). The outer aqueous phase contains 10 wt% partially hydrolyzed poly(vinyl alcohol) (PVA) ($M_w = 13–23$ kDa) to stabilize the emulsion drops. These drops are injected into the squeezing device using volume-controlled syringe pumps. We collect a mixture of double emulsion drops with thinner shells and single emulsion oil drops. The two types of drops can be separated by exploiting the density difference between the oil and the aqueous phase: The density of HFE-7500 is 1.6 times higher than that of water, and hence, the single emulsion drops sediment to the bottom of the collection. To make double emulsions float, they can be collected in an aqueous solution containing an appropriate amount of glycerol. In this case, the density of the collecting solution is significantly higher than that of the aqueous core of double emulsions. If the double emulsion shell, which is denser than the water/glycerol mixture, is sufficiently thin such that its volume fraction is small, the average density of the double emulsions is lower than that of the water/glycerol mixture. As a result, double emulsions float, while single emulsion oil drops. The two types of drops can conveniently be separated.

The viscosity of the oil is quantified with a DHR3 Rheometer using the coaxial cylinder geometry (TA Instrument). We vary the shear from 0.1 to 100 s$^{-1}$, keeping the strain constant at 1%.

3 Results and discussion

We inject a solution containing solely double emulsion drops with an outer diameter of $84 \pm 0.8 \mu m$ and a shell thickness of $5.2 \pm 0.2 \mu m$ into the squeezing device, as shown in the optical micrographs in Fig. 1a, b. These double emulsions are pushed through a microfluidic squeezer, schematically shown in Fig. 1c. The collected solution contains equal numbers of single and double emulsion drops. The size distributions of the single and double emulsion drops are very narrow, yet their diameters are distinctly different, as exemplified in the optical micrograph in Fig. 1d. Because the density of the double emulsion drops is different from that of single emulsion drops, they can be separated in the collection vial if it contains a liquid with an intermediate density, as detailed in the experimental section.

The shells of collected double emulsions are much thinner than those of injected drops. To investigate the mechanism by which single emulsion oil drops form at the expense of the shell thickness of the double emulsion drops, we visualize their flow through constrictions using a high-speed camera operated at 3000 frames per second. Because the drop diameter is larger than the channel height, they are deformed as soon as they enter the main channel. Remarkably, the deformed double emulsion drop is not symmetric. Instead, the center of the aqueous drop is located further upstream compared to that of the oil drop, resulting in an offset of the two drop centers, $O$, as shown in the inset of the optical micrograph in Fig. 2a. Once the drop is pushed into the constriction, it deforms even more, as shown in time-lapse optical microscopy images in Fig. 2a. At some point, it deforms so strongly that the leading end of the drop that is exclusively composed of oil is pinched off. The resulting single emulsion oil drop is completely detached from the double emulsion drop, whose shell thickness is significantly reduced, as shown in Fig. 2a and movie S1.

To investigate the reason for the offset of the two drop centers of the deformed double emulsions, we consider the pressure distribution within these drops. For drops contained in a microfluidic channel under laminar flow conditions, the pressure at their leading end is lower than that at their tailing end (Sajeesh et al. 2014). This pressure difference drives fluid flow inside the double emulsion drop. The resulting fluxes of the inner aqueous phase and the middle oil phase, $q_w = \frac{\Delta p}{R_{H,w}}$ and $q_o = \frac{\Delta p}{R_{H,o}}$, are inversely proportional to their hydrodynamic resistance, which we approximate to be that in a rectangular channel, $R_{H,n} = \frac{12h}{wH n L} \frac{1}{\mu} \frac{1}{\mu}$, here $\mu, h, L$ is the dynamic viscosity of the fluid, $L$ the length of the channel, $w$ its width, and $h$ its height (Leal 2007). The viscosity of the oil is 8 times lower than that of the PEG-containing aqueous phase such that the hydrodynamic resistance for the oil to flow is 8 times lower than that for the aqueous phase. Hence, the oil flows much faster toward the leading end of the double emulsion than the aqueous phase does, resulting in the offset of the two drop centers, as shown in Fig. 2a. This offset is required to pinch a single oil drop off the leading end of the double emulsion drop. However, this offset is not a sufficient condition for the drop pinch-off to actually occur.

The injected double emulsion drops only split into a double emulsion with a thinner shell and a single emulsion oil drop if they are strongly deformed inside the constriction. We expect this deformation to be caused by the shear stress that acts on the drop while it passes this constriction. To investigate the influence of the shear stress on the drop deformation, we vary the shear stress, $\tau \approx \mu_o \nu \left( \frac{1}{w} + \frac{1}{h} \right)$, by changing fluid flow velocity in the constriction, $\nu$, while we keep the other parameters constant; here $\mu_o$ is the dynamic viscosity of the continuous phase. To quantify the drop deformation, we estimate the drop surface...
area; because the diameter of the drop is much larger than the channel height such that it is strongly deformed in this direction, we approximate its cross section as a rectangle. We measure the projected perimeter of the drop from optical micrographs and multiply this value with the device height, as shown in Figure S1a. Using this approximation, we calculate the difference in surface area of a drop when deformed, $A_d$, and at rest, $A_0$, normalized by $A_0$, $\frac{\Delta A}{A_0} = \frac{(A_d - A_0)}{A_0}$; $A_d$ is measured when the drop is maximally deformed before the oil is pinched off, as shown in Figure S1b. For velocities above 4 cm/s, $\frac{\Delta A}{A_0}$ only weakly depends on $v$: It decreases by 10% if $v$ is increased by a factor of 2.5, as shown in Fig. 3a. This result indicates that there is a characteristic deformation above which double emulsion drops split into two drops. This deformation is reached if $v \geq 4$ cm/s. By contrast, if $v < 4$ cm/s, the shear stress is too low to deform the double emulsion drop sufficiently to cause pinch-off of a single emulsion oil drop. For example, if $v = 3.6$ cm/s, the normalized drop surface only increases by 40%. This increase in surface area is insufficient to cause detachment of an oil drop such that the shell thickness of the double emulsion drop remains unchanged upon

**Fig. 2** Optical time-lapse micrographs of double emulsion drops that flow through a 40-µm-wide and 60-µm-tall constriction at a flow rate of a 260 µL/h, b 150 µL/h, and c 3750 µL/h. The inset in (a) defines the offset $O$ of the center of the outer oil drop (red) and the inner aqueous drop (blue)
squeezing, as shown in the time-lapse optical micrographs in Fig. 2b and movie S2.

An increase in the deformation of a drop increases its interfacial area and therefore its interfacial energy. If the deformation is sufficiently high, we expect the system to be able to minimize energy by splitting the drop into two as this lowers the total interfacial energy (Deng et al. 2013). To test this expectation, we estimate the changes in interfacial energies involved in the deformation by multiplying the total surface area with the interfacial tension of the fluorinatated oil and water, \( \gamma = 5 \text{ mN/m} \). To test whether we can assume the interfacial tension to be in equilibrium while drops pass the constriction, we calculate the time for a surfactant to diffuse 20 nm, which is the length of a stretched surfactant molecule, using the diffusion coefficient for the perfluorinated surfactant in HFE-7500 (Brosseau et al. 2014). This diffusion time is \( 10^6 \) times lower than the time it takes to deform the drop. Hence, we assume the interfacial tension to always be in equilibrium. While the drop passes the constriction, its interfacial area increases by up to 90% compared to that of a drop at rest. This corresponds to an increase in the interfacial tension of 8.5 \( \times \) 10\(^{-11}\) J. This energy is equivalent to the interfacial energy of a spherical drop with a diameter of 84 \( \mu \)m at rest. In this case, the interfacial energy of the highly deformed double emulsion drop, \( E_d = \gamma A_d \), is higher than the sum of the interfacial energy of the double emulsion drop with a thinner shell and the single emulsion drop, \( E_s \), as shown in Fig. 3b and detailed in the SI. Hence, it is energetically favorable to detach a single emulsion drop from the shell of a highly deformed double emulsion drop. By contrast, if \( E_d < E_s \), no oil drop detaches, as observed in Fig. 2b, which corresponds to the first data point in Fig. 3b. These results suggest that drop detachment is thermodynamically driven.

Drops deform because they are subjected to shear stresses. If the deformation of the double emulsion drop scales with the shear stress and therefore the fluid velocity in the constriction, we should be able to predict the minimal velocity, \( v_t \), below which no drop detaches. Drops start to detach if the interfacial energy of the deformed drop is equal to the sum of the separated single and double emulsion drops. We expect the energy required to deform an injected drop, \( \Delta E = E_d - E_s \), to scale with the product of the shear stress and the constriction volume, as detailed in the SI. Using this energy balance and volume conservation, we obtain \( v_t = \frac{\pi \gamma h w}{\mu l^2 (w^2 + h^2)} \left[ (R + t)^2 - (R + t_0)^2 + ((R + t_0)^3 - (R + t)^3)^{\frac{1}{3}} \right] \); here \( l \) the length of the constriction, \( R \) the inner radius of the double emulsion drop, \( t_0 \) the shell thickness of the initial, and \( t \) that of the squeezed double emulsion drop. Using this formula, we can calculate \( v_t \) to be 5.8 cm/s, which is in fair agreement with the experimentally observed threshold value of 4 cm/s.

The shell thickness of double emulsion drops can usually be controlled with the fluid flow rates. To test whether this is also the case for double emulsions that have been squeezed through a constriction, we quantify the shell thickness, \( t \), as a function of the fluid velocity in the constriction \( v \). Because this thickness is below the resolution limit of an optical microscope, we measure the outer diameter of the double emulsion drop. We subsequently rupture this drop with isopropanol and measure the diameter of the resulting oil drop from optical micrographs. Using these two diameters and volume conservation, we can calculate the shell thickness, as shown in Figures S2 and S3 and detailed in the SI. To test whether the presence of isopropanol affects the volume of the oil drop, we quantify the shell thickness of double emulsion drops that have not been squeezed using optical microscopy; this is achieved by compressing them to different degrees and measuring the resulting changes in shell the thickness (Arriaga et al. 2015). To further validate this method, we measure the

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Fig. 3 a Relative change in surface area normalized by the initial surface area, \( \Delta A/A_0 \), as a function of the velocity of the continuous phase in the constriction, \( v \). b Difference in the interfacial energy of the maximally deformed injected double emulsion drop, \( E_d \), and the sum of the interfacial energies of the double emulsion drop with a thinner shell and the single emulsion drop, \( E_s \), as a function of \( v \) for injected double emulsions with a diameter of 84 \( \mu \)m that are pushed through 20-\( \mu \)m-wide and 60-\( \mu \)m-tall constrictions.
outer diameter of drops and calculate their shell thickness using the drop generation frequency measured from time-lapse optical micrographs, and the flow rate of the middle phase used to assemble these double emulsion drops, as detailed in the SI. All three methods result in very similar values, as shown in Figure S3, indicating that the presence of isopropanol does not significantly influence the calculated shell thickness. Because the use of isopropanol to rupture double emulsions is the most sensitive method to determine shell thicknesses, we use this method to determine all shell thicknesses.

The shell thickness of the collected double emulsion drops depends on the fluid velocity in the constriction. If double emulsions are pushed across the constrictions at $v$ below 4 cm/s, no oil is removed and the shell thicknesses of the squeezed double emulsions are equal to those of the injected ones. By contrast, if double emulsions are pushed across the constriction at $v \geq 4$ cm/s, oil is removed such that their shell thicknesses decrease while they are squeezed. Remarkably, the amount of oil that is removed during the squeezing process decreases with increasing $v$ for $v \geq 6$ cm/s. As a result, the shells of squeezed double emulsions are thinnest if they are pushed across at 4 cm/s < $v$ < 6 cm/s, as shown in Fig. 4a.

To investigate the reason for the increase in shell thickness with increasing $v$ for $v \geq 6$ cm/s, we increase $q$ even more to 3750 µL/h, corresponding to $v = 112$ cm/s and visualize the squeezing of drops with a high-speed camera. In this case, the positions of the centers of the inner aqueous and the outer oil drops are nearly identical and no large oil drop can detach. Instead, many much smaller oil drops are sheared off the surface of the double emulsion drop, as shown in the time-lapse optical micrographs in Fig. 2c and movie S3. To determine the reason for this change in the formation of oil drops, we quantify $O$ using optical micrographs and plot it as a function of $v$. The offset decreases with increasing $v$, as shown in Fig. 4b. This decrease in $O$ is related to a change in the complex fluid flow inside the drop, which depends on parameters such as the drop size relative to the channel geometry, the capillary number, the viscosity ratios, and the interfacial tension (Kinoshita et al. 2007; Ma et al. 2014). Another contributing reason for the decrease in $O$ with increasing $v$ is a change in the driving force for fluid contained in the drop to flow toward its leading end: The pressure gradient $\Delta p$ around the double emulsion drop decreases with increasing $v$. This decrease in $\Delta p$ is caused by the decrease in the hydrodynamic resistance experienced by the continuous phase that is locally induced by the presence of a drop in the microfluidic channel, with increasing $v$ (Sajeesh et al. 2014). Hence, the difference in the induced resistance of the aqueous phase $R_{H,w}$ and the oil phase $R_{H,o}$ inside the double emulsion drops decreases with increase in $v$, such that the offset of the drop centers decreases with increasing $v$. As the drop center offset becomes smaller, less oil can detach and the thickness of the resulting double emulsion increases, as shown in Fig. 4c. Hence, there is an optimum flow rate where drops are sufficiently deformed for an oil drop to detach, yet where the offset of the two centers is still large enough such that a high fraction of the oil is pinched off.

The final shell thickness of the squeezed double emulsion depends on the volume of oil contained in the injected
double emulsion drop upstream its neck that eventually results in the pinch-off of a single emulsion oil drop. This oil will remain in the shell of the squeezed double emulsion, and hence, it will determine its final shell thickness. Because the neck is always located at some distance apart from the interface of the innermost aqueous phase, there will always be some oil that remains in the shell of squeezed double emulsions. We expect the fraction of oil contained upstream the neck of the deformed double emulsion to increase with decreasing offset of the two drop centers. This offset depends on the difference in the hydrodynamic resistance experienced by the inner aqueous phase and the oil phase, and hence, it should scale with the ratio of their viscosities. Because in our case, the viscosity of the oil phase is lower than that of the aqueous phase, we expect the offset to become smaller with increasing oil viscosity, resulting in increased shell thicknesses of squeezed double emulsions. To test this expectation, we increase the viscosity of the oil by adding different amounts of Krytox™ GPL, a more viscous fluorinated oil, to HFE-7500, as shown in Figure S4. Indeed, the shell thickness of squeezed double emulsions increases with the viscosity of the oil, as shown in Fig. 4d.

The amount of oil that is removed from the shell of double emulsions while they are squeezed depends on the extent of their deformation. This deformation can be tuned with the operation parameters, such as the velocity with which double emulsions pass the constriction. Moreover, it can be tuned with the composition of the double emulsion, such as the viscosity ratios of the oil and the continuous phase. However, maybe the easiest way to control the drop deformation is by controlling the constriction geometry. To test whether we can indeed control the shell thickness of squeezed double emulsions with the constriction geometry, we fabricate devices with heights between 40 and 100 µm, keeping their width constant at 20 µm. We inject double emulsion drops with $5.2 \pm 0.2$-µm-thick shells and measure their minimal thickness, $t_{\text{min}}$, after their passage through the constriction as a function of its height. Their shell thickness decreases from 1.34 µm for $h = 100$ to 0.330 µm for $h = 40$ µm, as shown by the squares in Fig. 5a. Similarly, if we increase $w$ to 40 µm, the shell thickness increases with increasing height, albeit these shells remain thicker, as shown by the circles in Fig. 5a.

To relate the drop deformation to the oil removal, we plot the final shell thickness, $t$, normalized by the initial shell thickness, $t_0$, as a function of the deformation index, $D.I. = \frac{(L_d - w_d)}{(L_d + w_d)}$; here $L_d$ is the length and $w_d$ the width of the drop at its maximum deformation, as shown in the inset in Fig. 5b. When $D.I. = 0$, the drop is at rest; otherwise, $D.I. > 0$ (Sajeesh et al. 2014). As expected, the relative shell thickness decreases with increasing drop deformation, as shown in Fig. 5b. This result indicates that the volume of oil located upstream the neck that results in the pinch-off of the oil drop decreases with increasing deformation. Our result could indicate that the distance between the neck and the interface of the innermost aqueous drop decreases with increasing drop deformation. However, our result could also indicate that the offset of the two drop centers increases with increasing drop deformation such that more oil is located at the leading end of the injected double emulsion. To investigate the reason for the decrease in shell thickness with increasing drop deformation, we quantify the offset of the drop centers at the point of maximum deformation of the outer drop, $O_m$, immediately before the oil drop is pinched off, as a function $L_d$, as detailed in Figure S1b. The offset increases with $L_d$, as shown in Fig. 5c, indicating that a stronger deformation results in an increased offset of the two drop centers, which enables pinching off a larger oil drop from the leading end of the double emulsion drop.

Our results indicate that the amount of removed oil scales with drop deformation. This deformation depends on the ratio of the double emulsion diameter to the constriction dimensions. However, we expect it to be independent
of the initial shell thickness. To test this expectation, we produce 92-µm-diameter double emulsion drops with shell thicknesses varying between 5 and 9 µm. Indeed, in all cases, the shell thickness after squeezing is proportional to the initial shell thickness as seen in Fig. 6a, such that the relative change in the shell thickness is independent of the initial shell thickness, as shown in Fig. 6b. In all cases, approximately 93 vol% of the oil is removed. Importantly, this procedure is not limited to the removal of fluorinated oils, but it can also be applied to remove hydrocarbon-based oils, such as toluene, as demonstrated in movie S4. Hence, this device constitutes an efficient tool to remove the vast majority of oil from the shell of double emulsion drops, thereby enabling the production of drops with shell thicknesses well below 500 nm in an experimentally easy, reproducible process.

4 Conclusions

We present a microfluidic squeezing device that splits double emulsion drops into equal numbers of double emulsion drops with much thinner shells and single emulsion oil drops. Therefore, this device enables removal of up to 93 vol% of the oil, resulting in double emulsions with shell thicknesses down to 330 nm. As this oil removal relies on a pinch-off of a single emulsion drop from the double emulsion shell, any oil, including those that are non-volatile or have no solubility in water whatsoever, can be removed. Hence, this method constitutes an experimentally easy, versatile way to controllably and efficiently reduce the shell thickness of a wide range of double emulsions including those composed of biocompatible oils such as fluorinated oils. These double emulsions can be used as templates to make capsules with very thin shells whose composition is determined by that of the oil. Thus, this device has the potential to produce mechanically stable capsules with thin shells made from a much broader range of materials than is currently possible.

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Fig. 6  a Influence of the initial shell thickness, $t_0$ on the shell thickness after drops have been pushed through a 20-µm-wide, 60-µm-tall constriction, $t$. For each constriction, drops are injected at the optimum flow rate where most oil is removed. b Percentage of oil removed from double emulsion drops for different initial shell thicknesses, $t_0$, if pushed through a 20-µm-wide, 60-µm-tall constriction. Drops are pushed through the constriction at the optimum flow rates where most oil is removed.
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