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Two phase microfluidics with inviscid drops: Effects of total flow rate and delayed surfactant addition

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ABSTRACT

The microfluidic production of droplets is a well controllable process, which allows templating small spherical containers that can subsequently be transferred into uniformly sized polymer microgel particles by a crosslinking reaction. Recently, the per-channel production rate of *N*-isopropylacrylamide (NIPAAm) droplets (w-phase) dispersed in a low-viscosity fluorocarbon oil (o-phase) could be increased by a delayed surfactant addition, while maintaining the advantageous dripping regime. Here it should be evaluated, if delayed surfactant addition can be applied to enhance droplet production also for high viscosity continuous phases, which is associated with a change to an inviscid drop scenario compared to the previously used setting of viscous drops. It could be illustrated that the concept of delayed surfactant addition holds true also for viscous continuous phases and allows ~8 fold increased flow rates in the dripping regime. Surprisingly, the droplet size increased at higher total flow rate with constant flow rate ratios of w- and o-phases, which is discussed in the light of viscous dissipation, microchannel bulging and viscosity of the continuous phase. More rigid microchannels such as from glass may allow further exploring this phenomenon in the future.

INTRODUCTION

Microfluidic preparation allows obtaining uniformly sized droplets in a process driven by interfacial instabilities in a flow field rather than by external actuation. Using a flow focusing geometry, a stream of the inner phase 1 is contacted and squeezed by the continuous phase 2, resulting in thinning and eventually break-up of the thread of phase 1 [1]. This process is performed in laminar flow conditions and is well controllable, e.g. by the geometry of microchannels used to build the microfluidic device or the flow rates Q_1 and Q_2 of the disperse phase 1 and the continuous phase 2, respectively. Droplets prepared in this manner can be subsequently modified in the microfluidic channel such as by splitting, merging with other droplets, deformation, or can be subjected to chemical reactions of components dissolved in the disperse phase such as monomers or oligomers to synthesize polymer network structures [2] [3]. Such swollen polymer networks formed within each droplet are termed as microgels, which are considered to encapsulate sensitive compounds or cells and can show stimuli-sensitivity, e.g. temperature-induced changes in particle size as in case of poly(*N*-isopropylacrylamide) (PNIPAAm)-based systems [3].

Compared to bulk emulsification processes, where mixers in industrial vessels can produce large quantities of particles with a broad particle size distribution, the microfluidic production of particles drop-by-drop in the dripping regime allows monodispersity but has limitations in the

throughput. Besides some other strategies based e.g. on multiple channels operated at a time or multiplication of droplets by droplet-splitting [4], recently the concept of delayed surfactant addition was proposed [5]. This approach bases on maximizing the interfacial tension σ between phase 1 and 2 by omitting surfactants at the time of droplet formation. Subsequently, a surfactant-rich oil phase 3 is added further downstream in the microfluidic flow-focusing device for droplet stabilization. In this manner, two relevant parameter that affect dripping-to-jetting transition, the Weber number We of the inner phase 1 and the capillary number Ca of the continuous phase 2, can be modified (Eq. 1 and 2, η = dynamic viscosity, \dot{V} = fluid velocity, ρ = density of the respective fluid, d = channel diameter, σ_{12} = interfacial tension between the phases 1 and 2). This allows increasing the in-channel velocity (mass throughput) while maintaining the advantageous dripping regime, which typically occurs when either number or their sum adapts values of about or below unity [6].

$$We = \frac{\rho_1 \cdot \dot{V}_1^2 \cdot d}{\sigma_{12}} \quad (1)$$

$$Ca = \frac{\eta_2 \cdot \dot{V}_2}{\sigma_{12}} \quad (2)$$

It was previously confirmed that the per-channel productivity of *N*-isopropylacrylamide (NIPAAm) droplets can be increased by delayed surfactant addition using a relatively expensive, low-viscosity fluorocarbon oil (HFE) as phase 2/3 [5]. It remains to be shown if this concept holds true also for other continuous phases such as paraffin oil that is better compatible with industrially concerns of production costs. Changing the phase 2 to a viscous oil, however, substantially affects the viscosity ratio $\lambda_{12} = \eta_1 \cdot \eta_2^{-1}$ as a dimensionless parameter. In case of NIPAAm/HFE [5], $\lambda_{12} \sim 1$ and the drops are “viscous”. In contrast, for a continuous phase of higher viscosity as should be used here, $\lambda_{12} \ll 1$ will result in “inviscid” drops with substantial alterations of the pressure distribution and pressure drop in the microfluidic channel [1]. Furthermore, Ca will increase according to Eq. 2, which emphasizes the scientific question if delayed surfactant addition can be a feasible approach to increase per-channel productivity of microfluidic droplet templating with viscous paraffin oil as continuous phase.

EXPERIMENTAL

Materials

The employed materials included: high viscosity hydrocarbon paraffin oil (Carl Roth GmbH, Karlsruhe, Germany; Catalog No. #8904.1, determined properties see Table 1), surfactant ABIL EM 90 (Evonik Goldschmidt, Essen, Germany), *N*-isopropylacrylamide (NIPAAm, 97%), *N,N'*-methylene bisacrylamide (BIS, 99%) and ammonium persulfate (APS, 98%) (all latter by Sigma-Aldrich, Steinheim, Germany). Microfluidic devices with a flow focusing geometry as shown in Fig. 1 were built by soft lithography as an array of channels in a polydimethylsiloxane (PDMS) matrix bonded to a glass slide (for details, see [5]). The dimensions of PDMS-devices with two subsequent junctions were 40 x 40 μm^2 for the feeding channel, 40 x 40 μm^2 for the first collection channel after the first junction, and 80 x 40 μm^2 (width x height) after the second junction. In control studies, single junction PDMS-devices with 50 x 50 μm^2 feeding channels and a 50 x 50 μm^2 collection channel were used.

Methods

The phases 1 (phase to be dispersed; containing 98 g L⁻¹ NIPAAm, 2 g L⁻¹ BIS, 5 g L⁻¹

APS), phase 2 (direct surfactant addition: paraffin oil with 5% v/v ABIL EM 90; delayed surfactant addition: pure paraffin oil), and phase 3 (direct surfactant addition: pure paraffin oil; delayed surfactant addition: paraffin oil with 5% v/v ABIL EM 90) were fed by syringe pumps (AL 1010, WPI, Sarasota, FL, USA) to the microfluidic devices. In all experiments, the flow rates Q of each phase given in $\mu\text{l}\cdot\text{h}^{-1}$ were equal $Q_1 = Q_2 = Q_3$ and systematically increased. A digital high-speed microscope (VW 6000E with VH-Z100R lens and VW 100C camera, Keyence Deutschland GmbH, Neu-Isenburg, Germany) was used to observe droplet formation. The interfacial tension σ_{12} and the density ρ of the respective phases were determined by a tensiometer (K 100, Krüss GmbH, Hamburg, Germany) with either Wilhelmy-plate (P101) or the density measurement set (DE0701) with a precision of $\Delta\sigma_{12} = 3 \cdot 10^{-3} \text{ mN}\cdot\text{m}^{-1}$ and $\Delta\rho = 3 \cdot 10^{-3} \text{ g}\cdot\text{mL}^{-1}$. To determine the kinematic viscosities ν , an Ubbelohde viscometer with Hagenbach correction (PVS1, S5 test stand, E200 thermostat, Koenigshofen, Germany) with an accuracy of $\Delta\eta = 0.2\%$ was employed and dynamic viscosities (η) were calculated by $\eta = \nu \cdot \rho$.

RESULTS AND DISCUSSION

In order to overcome the limitation of slow droplet production in the dripping regime and apply the concept of delayed surfactant addition to application-relevant paraffin oil, the dripping-to-jetting transition was studied in a PDMS flow-focusing device equipped with three inlets. In the first inlet, the aqueous phase 1 (NIPAAm monomer solution) was introduced, which should be dispersed to form a “water-in-oil” emulsion. At the inlets two and three, the oil phases 2 and 3 were provided, which both based on the same paraffin oil. When operating in the conventional mode with direct surfactant addition, both phase 2 and 3 contained surfactant. Alternatively, in case of delayed surfactant addition, phase 2 was pure paraffin oil. Surfactant for droplet stabilization was added only at the second junction and thus timely/spatially separated from the point of droplet formation in the flow field. Table I illustrates the interfacial tension, which substantially decreased by addition of surfactant (ABIL EM 90) to the continuous phase. Table I confirms that paraffin oil has a substantially higher viscosity than the monomer solution. Thus, the above mentioned condition of inviscid droplets with $\lambda_{12} \ll 1$ is fulfilled.

When operating the microfluidic device with direct surfactant addition at increasing flow rates $Q_1 = Q_2 = Q_3$, a transition from the dripping regime towards the jetting regime was observed. The jetting regime is typically associated with an undesirable increase of the droplet size distribution and thus should be avoided. Importantly, jetting of the NIPAAm phase occurred at relatively low $Q = 200 \mu\text{L h}^{-1}$ when direct surfactant addition was performed (Fig. 1A).

Table I: Viscosities, densities and interfacial tensions of the employed fluids at 25 °C.[#]

Fluid	ν ($\text{mm}^2\cdot\text{s}^{-1}$)	ρ ($\text{g}\cdot\text{mL}^{-1}$)	η ($\text{mPa}\cdot\text{s}$)	σ_{12} [§] (mN m^{-1})
Monomer solution ^{§,*}	1.29	1.399	1.80	n.a.
Hydrocarbon Paraffin oil	166	0.874	145	15.0
Hydrocarbon Paraffin oil w/surfactant	172	0.875	151	0.37

[#] Determined by Ubbelohde viscosimeter (ν : $n = 5$ repetitions) and tensiometer (ρ : $n = 20$ repetitions; σ_{12} : $n = 5$ repetitions) with precisions as given in the methods section. [§] Containing *N*-isopropylacrylamide (NIPAAm, 98 g L^{-1}), *N,N'*-methylene bisacrylamide (BIS, 2 g L^{-1}), ammonium persulfate (APS, 5 g L^{-1}). [§] σ_{12} of monomer solution and paraffin oil w/o or w/ surfactant (2.5% v/v). n.a. not applicable *Data reproduced from [5] with permission.

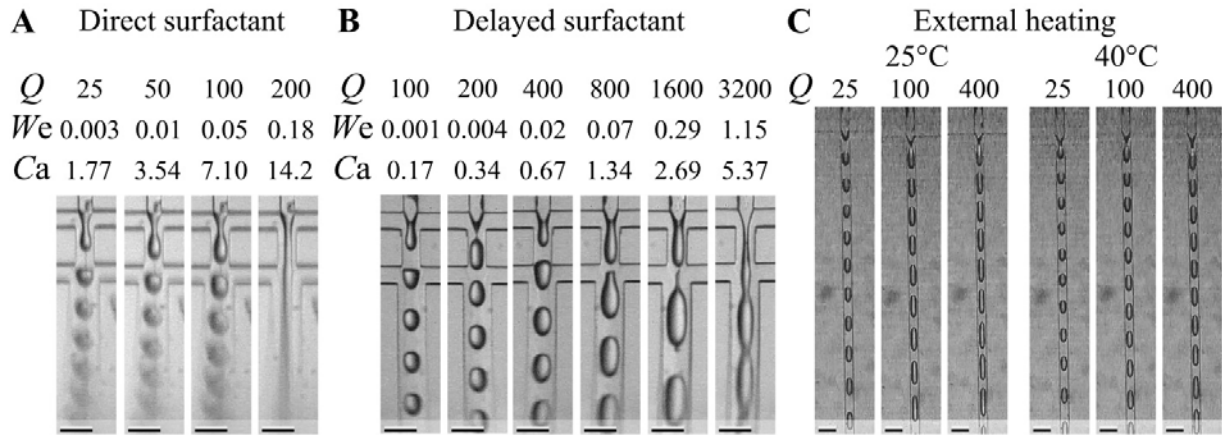


Fig. 1: Dripping-to-jetting transitions in microfluidic emulsification of NIPAAm/paraffin oil. The inner phase is an aqueous monomer solution of 98 g L^{-1} NIPAAm, 2 g L^{-1} BIS, and 5 g L^{-1} APS, whereas the continuous phase is high viscous paraffin oil along with (A) direct or (B) delayed addition of surfactant ABIL EM 90 in the same oil (5% v/v). (C) Effect of elevated temperature studied in control experiment with single junction device and no surfactant addition. Q = volumetric flow rate of each phase $Q_1 = Q_2 = Q_3$ ($\mu\text{L}\cdot\text{h}^{-1}$); We = Weber number given for phase 1; Ca = Capillary number given for phase 2. All scalebars $100 \mu\text{m}$.

According to Eq. 1 and 2, $Ca_{200 \mu\text{L/h}} = 14.2$ and $We_{200 \mu\text{L/h}} = 0.18$ can be determined for this flow condition, which clearly exceed unity as characteristic mark for dripping-to-jetting transition in a logarithmic dependency.

However, when delayed surfactant was applied, the dripping-to-jetting transition was shifted to $v = 1600 \mu\text{L h}^{-1}$. This corresponds to $Ca_{1600 \mu\text{L/h}} = 2.7$ and $We_{1600 \mu\text{L/h}} = 0.29$ (Fig. 1B) as calculated from the fluid properties in the absence of surfactant (Table I). Delayed surfactant addition allowed to increase the volumetric flow rate for controlled pre-microgel droplet formation by a factor of 8 due to the inverse proportionality of σ_{12} and Ca and We , respectively. This is comparable to the effect observed when using HFE oil [5]. This confirms that the principle of delayed surfactant addition is applicable also to a setting of inviscid droplets, even though the productivity may be lower due to the effect of high viscosity continuous phases on Ca according to Eq. 2.

An interesting observation for the inviscid droplet scenario is an increase in droplet size at high flow rates. It is well known that droplet size typically increases in flow focussing devices when the flow rate ratio $q_{12} = Q_1 \cdot Q_2^{-1}$ is increased [7]. However, in the present example, $Q_1 = Q_2 = Q_3$ was applied in all cases, i.e. q_{12} was maintained constant. It was previously observed that the diameter D of formed droplets can become larger at higher temperature T according to Eq. 3, at least for phase 2 solvents with strong temperature-dependent variation of η_2 but only a moderate variation of σ_{12} [8]. One reported example is water dispersed in mineral oil (phase 2), which apparently was used without surfactant and showed a doubling in droplet volume when the temperature was increased from $20 \text{ }^\circ\text{C}$ to $40 \text{ }^\circ\text{C}$ [8].

$$D(T) \propto Ca^{-1} = \frac{\sigma_{12}}{\eta \cdot v} \quad (3)$$

Since microfluidic systems are typically run without external temperature control, elevated local temperatures may be induced in the flow channel by viscous dissipation at high flow rates.

Simulation studies suggest that e.g. for water flowing in 40 μm tubes, temperatures rises of several Kelvin are possible at least in adiabatic conditions and at high velocity [9].

$$\Delta P = (R_1 + R_2 + R_n) \cdot Q, \text{ with } R = \frac{128 \cdot \eta \cdot L}{4 \cdot A \cdot \varphi \cdot D_h^3} \text{ and } \varphi \approx \frac{2}{3} + \frac{11}{24} \cdot AR \cdot (2 - AR) \quad (4)$$

$$\Delta \langle T \rangle = \frac{\Delta P}{\rho \cdot c_p} \quad (5)$$

Here, as a simplification, the presence of drops in microfluidic channels should be neglected, considering only the properties of the pure viscous phase 2 in the given microfluidic geometry as well as the total flow of phase 1+2 at the first junction. The local heating may be estimated according to Eq. 6 [10] and 7 [11], considering the pressure drop ΔP in the device to be composed of a sum of flow resistance R , where here only the relevant region L between the first and second junction should be included (channel cross section area A ; aspect ratio factor φ with aspect ratio $AR = 1$ for square channels; $Q_{1+2} = 3200 \mu\text{l} \cdot \text{h}^{-1}$). The resulting $\Delta P = 143 \text{ kPa}$ from Eq. 4 corresponds, in an adiabatic flow, to an average temperature increase $\Delta \langle T \rangle$ of only 0.074 K (Eq. 5). Even though local temperatures may substantially exceed this $\Delta \langle T \rangle$ and ΔP may be underestimated by neglecting the contribution of inviscid drops to ΔP [1], it may still be concluded that local heating by viscous dissipation remains $< 1 \text{ K}$.

In order to experimentally evaluate potential temperature effects on droplet formation at different $Q_1 = Q_2$, a control experiment was conducted using a flow focusing device with only one junction and a long downstream channel ($D_h = 50 \mu\text{m}$) mounted on a heating plate. As shown in Fig. 1C, only higher $Q_1 = Q_2$ but not external heating resulted in increased droplet size. This generally suggests that temperature may not account for the observed phenomenon.

An alternative explanation may base on the role of device geometry on droplet pinch-off. PDMS devices do not behave ideally in terms of rigidity of the channel walls, but are elastic with a Young's modulus in the range of 1 MPa [12]. PDMS microchannels can show bulging – with A increased highest in front of the resistor R [13], i.e. here the collection channel at the point of droplet formation. In a glass-bonded PDMS channel, a deformation would mainly occur towards larger channel depth, which may have allowed larger drops to form at higher Q . Based on the short periodic pressure increases associated with each inviscid drop formation for incompressible Newtonian fluids [1, 14], it may be further speculated, if the general channel deformation may be overlaid by an oscillatory deformation allowing short-term fluid storage and a pulsatile flow in the channel similar to blood vessels, additionally contributing to alteration of droplet size. The elongation of droplets already during pinch-off without contacting the channel wall (Fig. 1A-B) may be due to the presence of a viscous strata that was shown to increase in thickness in confined conditions at high \dot{V} with high viscosity continuous phases, i.e. increasing Ca (see Eq. 2) [15].

CONCLUSIONS

The concept of delayed surfactant addition allows emulsification in the dripping regime with increased throughput also for an inviscid droplet scenario with application-relevant viscous continuous phases. Energy dissipation and local heating due to the high viscosity of the continuous phase may not be a main cause for increased droplet sizes at high flow rates. The possibility of PDMS channel deformation, pressure oscillation, increased shear forces, and viscous strata formation may need to be considered when using high viscosity continuous phases at high flow

rates. More rigid microchannels such as from glass and experimental analysis of pressure drop and pressure fluctuations may allow further exploring this phenomenon in the future.

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