Droplet breakup driven by shear thinning solutions in a microfluidic T-Junction

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Droplet microfluidics is, like a miniaturized biomedical lab, efficient and adjustable for high throughput analysis, encapsulation of cells, drug formulation, polymerase chain reaction. Typically, for most biomedical applications, handling of complex, non-Newtonian fluids is involved, e.g. synovial and salivary fluids, collagen, gel scaffolds. The role of the corresponding rheology on the droplets breakup has not been accurately addressed so far. Here we suggest a novel approach to describe droplets formation occurring in a microfluidic T-shaped junction, either in Newtonian or non-Newtonian, shear thinning liquids. The non-Newtonian liquid carrying the droplets was made of Xanthan solutions, a stiff rod-like polysaccharide displaying a marked shear thinning rheology and weak elastic effects. The breakup process shows similar trends regardless of the nature of the surrounding liquid once the droplets size is assessed in terms of an effective Capillary number introduced to account for shear thinning effects. Experimental results are complemented with numerical simulations of pure power-law fluids with the lattice Boltzmann models, which are in good quantitative agreement with the experimental data and confirm the proposed scaling.

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I. INTRODUCTION

In the last decade, droplet-based microfluidics has been successfully applied to high-throughput chemical and biological analysis, synthesis of advanced materials, sample pretreatment, protein crystallization, encapsulation of cells or digital PCR systems [1-8]. It is common to refer to a fluid forming the droplets as to the dispersed phase, which is carried by the stream of a second, immiscible fluid identified as the continuous phase. Three main approaches are usually adopted to produce uniform trains of droplets [9-12]: (i) breakup in co-flowing streams, (ii) breakup in stretching- or elongational-dominated flows, and (iii) breakup in cross-flowing streams.

The breakup dynamics of the dispersed phase and the formation of droplets are relatively well understood in the case of two immiscible Newtonian fluids as, for example, water and oil [10,13]. More recently, this investigation has been extended to viscoelastic liquids because of a continuously increasing interest for the production of droplets in non-Newtonian liquids, where the viscosity changes with the applied stress [14]. These involve physiological fluids [15] such as blood (including fibrinogen to fibrin formation [16,17]) synovial or salivary fluids [18], as well as fluid jets in printing and spraying technology [19,20], food emulsions [21,22]. Most of the attention has been so far devoted to the formation of viscoelastic droplets carried by Newtonian continuous phases [23,24]. For elastic polymers, the effect of the molecular weight on filament thinning has been clarified in flow-focusing devices [25,26]. Recently, only a few studies considered droplets carried by viscoelastic medium. However, they explored either flow focusing geometries [14,27], or air bubbles formation [28]. An exhaustive description of the breakup mechanism driven by non-Newtonian continuous phases in T-shaped junction is still basically lacking.

In the present study we show a comprehensive and systematic study of the breakup in a microfluidic T-junction, when droplets are carried either by Newtonian or pure shear thinning liquids in different dynamical regimes (a very preliminary report of the experimental results has appeared elsewhere [29]). As non-Newtonian fluids, solutions of Xanthan, a stiff rod-like polysaccharide, are investigated. At the concentrations considered, they exhibit a well pronounced shear thinning behaviour with a finite thinning flow behaviour index and weak elastic effects due to the emergence of first normal stress differences at relatively high concentrations [30,31]. The droplet size is analyzed as a function of the flow properties in various dynamical regimes. Due to the shear thinning effects, the viscosity is non homogeneous in space and varies with the flow rates of the two phases. By quantitatively comparing Newtonian and non-Newtonian data, robust experimental evidence is provided that the droplet size rescales nicely with an effective Capillary number (Ca), which reduces to the usual Capillary number (Ca) when both liquids are Newtonian. Experiments are complemented with numerical simulations of purely thinning fluids based on the lattice Boltzmann models (LBM), which are in good quantitative agreement with
the experimental data and confirm the proposed scaling.

The paper is organized as follows: in Section II we present the experimental and numerical methodologies, and introduce the effective Capillary number. Experimental results are presented in Section III. In Section IV we show numerical results with pure thinning fluids. Conclusions and final remarks are reported in Sec. V.

II. MATERIALS AND METHODS

A. Experiments

Droplets are produced by merging two immiscible liquids in a microfluidic T-junction (Fig. 1A), which is composed of a main microchannel encountering perpendicularly a side channel, having the same cross section. The chips, with an overall size of 2 cm x 5 cm and microchannels of width W ~ 150 µm and height H ~ 100 µm, are made in PDMS (Polydimethylsiloxane, Sylgard 184, Dow Corning) using standard photo-softlithography. Further details about the fabrication can be found in Sec. I of the Electronic Supplementary Information (ESI).

The dispersed phase forming the droplets is injected by the side channel with a flow-rate Q_d, while the continuous phase carrying away the droplets is injected in the main channel with a flow-rate Q_c. The flow-rates being controlled by a couple of syringe pumps specifically designed for viscous flows (PHD 2000 from Harvard Apparatus, USA). Images of the droplets are acquired and analyzed in real-time with a custom made software, which also controls the syringe pumps. The length L of the droplets is measured, after breakup, in a region of interest downstream of the T-junction (Fig. 1A), and is averaged over at least a hundred droplets. Further details on the experimental setup are reported in Sec. II of ESI.

We address the generation of droplets both in Newtonian continuous phases (Newtonian system) and in shear thinning phases made of polymer solutions (non-Newtonian system). Table I summarizes the Newtonian fluids reporting the liquids composition, dynamic viscosity \( \eta_d \) of the dispersed phase, dynamic viscosity \( \eta_c \) of the continuous phase, viscosity ratio \( \lambda \) and interfacial tension \( \sigma \). The viscosity ratio is defined as the ratio between the dynamic viscosity of the dispersed phase and the one of the continuous phase \( \lambda = \eta_d/\eta_c \). The experiments span two decades of \( \lambda \) using various combinations of either Soybean oil (Alfa Aesar) or Hexadecane (Sigma Aldrich), and water solutions of Glycerol (≥ 99.5% anhydrous, Sigma Aldrich) at different concentrations. A surfactant is added to the continuous phase in order to improve the wetting of the channel walls. Triton X-100 (Sigma Aldrich) is used in the water solutions while Span 80 (Sigma Aldrich) is added to Hexadecane. The values of the interfacial tension \( \sigma \) are measured with the pendant droplet technique.

The non-Newtonian systems are summarized in Table II. Soybean oil is used as the dispersed phase while, as continuous phase, water solutions of Xanthan (molecular weight \( M_w \sim 10^6 \) g/mol, Sigma Aldrich) at different concentrations are employed. The concentration of polymers is chosen to ensure that the rheological response of the continuous phase is dominated by shear thinning rather than viscoelasticity. The viscosity data of the Xanthan solutions are fitted according to the power law fluid model, similarly to what have been performed in [29, 30]:

\[
\eta(\dot{\gamma}) = K \dot{\gamma}^{(n-1)}
\]

where \( K \) and \( n \), being the fluid consistency and the flow behaviour index respectively, are used as fitting parameters. Their values are listed in Table II for the considered concentrations of Xanthan.

The breakup process occurring in a microfluidic T-Junction, the droplet size is usually analyzed in terms of the Capillary number [5, 13, 35–37]:

\[
\text{Ca} = \frac{\eta_c U_{av}}{\sigma}
\]

where the quantities \( U_{av} \) and \( \eta_c \) refer to the average velocity and the viscosity of the continuous phase, respectively. In the case of a non-Newtonian continuous phase, \( \eta_c \) is chosen to be the value corresponding to an effective shear rate:

\[
\dot{\gamma}_{av} = \frac{3U_{av}}{W}
\]

The numerical prefactor 3 is fixed in such a way that for a Newtonian fluid driven by a pressure gradient \( \nabla P \) between two (no-slip) parallel plates at distance \( W \), the definition (3) coincides with the average shear developed in the system. Since \( U_{av} = Q_c/WH \), the value of the viscosity \( \eta_c(\dot{\gamma}_{av}) \) can be computed by the power law fluid model (1) in terms of \( Q_c \). Within the investigated range of \( Q_c \), the computed shear rates go from \( \sim 1 \) s\(^{-1}\) to \( \sim 2 \times 10^3 \) s\(^{-1}\). In the case of a shear thinning continuous phase, an effective Capillary number \( \text{Ca} \) is then introduced. A balance between viscous thinning effects and pressure gradients suggests that a proper definition of \( \text{Ca} \) is (see Sec. III of the ESI):

\[
\text{Ca}_n = n \left[ \frac{\eta_c(\dot{\gamma}_{av})U_{av}}{\sigma} \right]
\]

\( n \) being the flow behaviour of the power law fluid (see Eq. 1). In the case of a Newtonian fluid, the \( \text{Ca} \) reduces to the usual Ca number defined in Eq. 2 because \( n = 1 \) and \( \eta_c(\dot{\gamma}_{av}) \) is a constant.

B. Numerical Simulations

Our numerical simulations rely on lattice Boltzmann models (LBM). LBM are mesoscopic methods, tracking
TABLE I: Experimental parameters of the liquids of the Newtonian systems. All quantities refer to a temperature $T = 25^\circ C$. Surfactants and Glycerol concentration are expressed in terms of weight/weight ratio.

| ID  | Dispersed Phase    | Newtonian Continuous Phase         | $\eta_d$ (mPa·s) | $\eta_c$ (mPa·s) | $\lambda$ | $\sigma$ (mN/m) |
|-----|--------------------|------------------------------------|------------------|------------------|-----------|-----------------|
| N1  | Soybean Oil        | Water + 0.50% Triton X-100          | 49.1             | 0.9              | $\sim 50$ | 2.55 ± 0.03     |
| N2  | Soybean Oil        | Glycerol/Water 60% + 0.56% Triton X-100 | 49.1             | 9                | $\sim 5$  | 3.59 ± 0.27     |
| N3  | Glycerol/Water 67% | Hexadecane + 1% Span 80            | 14.5             | 3                | $\sim 5$  | 3.99 ± 0.11     |
| N4  | Glycerol/Water 40% | Hexadecane + 1% Span 80            | 3.22             | 3                | $\sim 1$  | 4.17 ± 0.03     |
| N5  | Water              | Hexadecane + 1% Span 80            | 0.9              | 3                | 0.3       | 5.01 ± 0.15     |

TABLE II: Experimental parameters of the liquids of the non-Newtonian systems. All quantities refer to a temperature $T = 25^\circ C$. The concentrations are expressed in terms of weight/weight ratio.

| ID   | Dispersed Phase    | Shear Thinning Continuous Phase   | $\eta_d$ (mPa·s) | $K$ (mPa·s$^n$) | $n$ | $\sigma$ (mN/m) |
|------|--------------------|-----------------------------------|------------------|-----------------|-----|-----------------|
| X400 | Soybean Oil        | Xanthan 400 ppm + 0.2% Triton X-100 | 49.1             | 32.6            | 0.589 | 3.42 ± 0.01     |
| X800 | Soybean Oil        | Xanthan 800 ppm + 0.2% Triton X-100 | 49.1             | 75.5            | 0.491 | 3.00 ± 0.04     |
| X1500| Soybean Oil        | Xanthan 1500 ppm + 0.7% Triton X-100 | 49.1             | 312.5           | 0.389 | 2.28 ± 0.02     |

the evolution in space and time of the probability distribution function for the particles, while the hydrodynamics of Navier-Stokes (NS) equations is recovered from the coarse-grained behaviour of the system. Its mesoscopic nature can provide many advantages over atomistic methods, making the LBM especially useful for simulation of droplet and interfacial dynamics. There are various LBM methodologies which have been adopted to investigate droplet dynamics and formation in the confined T-Junction geometries [36, 46]. In the early papers by Van der Graaf et al [38, 39] and also those by Alapati & Bower [40, 42], “free energy” based LBM were used to study Newtonian droplet formation, also in comparison with experiments [39]. LBM based on the “Shan-Chen” interaction models were instead used in the “Shan-Chen” interaction models were instead used in the coarse-grained behaviour of the system. Its mesoscopic nature can provide many advantages over atomistic methods, making the LBM especially useful for simulation of droplet and interfacial dynamics. There are various LBM methodologies which have been adopted to investigate droplet dynamics and formation in the confined T-Junction geometries [36, 46]. In the early papers by Van der Graaf et al [38, 39] and also those by Alapati & Bower [40, 42], “free energy” based LBM were used to study Newtonian droplet formation, also in comparison with experiments [39]. LBM based on the “Shan-Chen” interaction models were instead used in the study the various regimes induced by a change in the geometry, flow-rates and viscosity ratios [36, 43]. The LBM have already been applied to the simulation of non-Newtonian phases in microfluidic T-Junctions as well. Shi & Tang [49] used immiscible LBM to investigate the effects of non-Newtonian power-law fluids in confined T-Junctions. The final droplet size, droplet generation frequency, and detachment point of the droplet are found to change with the power-law exponent, thus showing the relevance of non-Newtonian power-law fluids. Our numerical work falls in the continuity of other papers by some of the authors [50, 51]. We have conducted 3D simulations to study the characteristic mechanisms of breakup in confined T-junctions [50, 51], showing that elastic effects can sensibly perturb the flow driving the breakup process and influence the droplet dynamics and the resulting size after breakup. The LBM code we use is essentially the very same employed in [40, 52], hence we refer the interested reader to those papers where all the relevant technical details are discussed (see also Sec. V of the ESI).

III. EXPERIMENTAL RESULTS

In the presence of a shear thinning continuous phase, we can still identify the breakup regimes commonly reported with Newtonian liquid [3, 5, 59] shown in the left snapshots of Fig. 1 at increasing Ca. In panel (A), droplets form at the junction and fill the channel assuming a plug shape. The dispersed phase completely obstructs the channel leading to an increase in the pressure upstream, which eventually breaks-up the interface into a droplet. In this “squeezing” regime the droplet size does not strongly depend on Ca, but only on the flow-rates [13, 35, 48, 55]. In panel (C) the droplets are emitted before they can block the channel and their formation is due to the action of the viscous shear stress. In this “dripping” regime, the droplet size decreases with Ca [10, 35, 55]. Finally, panel (F) shows that, at high Ca, the detachment point moves gradually downstream and the breakup process signals the emergence of a “jetting” mode [55]. The snapshots (B) and (E) show the intermediate cases right before the transition to dripping and jetting, respectively. The right snapshots of Fig. 1 refer to oil drops in Xanthan solutions. They clearly show that, by varying the flow-rate $Q_c$ of the continuous phase, it is possible to reproduce the same regimes reported for the Newtonian systems. Fig. 2 shows the dependence of the normalized droplet length $L/W$ as a function of the flow-rate $Q_c$ of the continuous phase (for Xanthan solutions) or both $Q_c$ and the Capillary number Ca (for Newtonian liquids) at different flow-rate ratios $\varphi = Q_d/Q_c$ and $\lambda$. The right snapshots of Fig. 1 refer to the Newtonian liquids whose details are listed in Table I while panels (G-I) correspond to the drops formed in shear thinning continuous phases described in Table II. These measurements provide a sig-
is not very pronounced because the width of the two in-
point out that, with our geometry the dripping regime
ations [48, 55]. For instance, at small Ca, the droplet size
consistent with previous studies performed in similar condi-
ations (Fig. 1-B) by increasing \( Q_c \), the jet persists
even after decreasing \( Q_c \).

The droplet size is observed to increase at increasing \( \varphi \), and decrease at increasing Ca [13, 55]. This trend is consistent with previous studies performed in similar conditions [13, 55]. For instance, at small Ca, the droplet size is independent of the viscosity ratio (see, for instance, the data at \( \varphi = 0.4 \) in Fig. 1-B-E) and increases with the flow-rate ratio (compare, for instance, the data at \( \varphi = 0.4 \) and \( \varphi = 0.6 \) in Fig. 1-B-E), in agreement with the scaling argument valid for the squeezing regime [13]. Furthermore, the change in the slope found at \( Ca \approx 10^{-2} \) for the curve \( \varphi = 0.2 \) and \( \lambda = 1 \) in Fig. 2-D (see dashed line) is very close to the transition from squeezing to dripping calculated in phase-field numerical simulations of immiscible fluids at \( Ca \approx 0.015 \) for \( \varphi = 0.25 \) and \( \lambda = 1 \) [35]. We point out that, with our geometry the dripping regime is not very pronounced because the width of the two in-
lets channels are the same [37, 47]. For droplets carried by shear thinning liquids, the droplet size is observed to increase with \( \varphi \) and to decrease with increasing \( Q_c \), just like the Newtonian counterparts. However, the size of the droplets produced in Xanthan solutions appears to increase at high \( Q_c \). A more accurate analysis of the images reveals that droplets volume actually decreases with increasing \( Q_c \) and the increasing of the droplet size at high \( Q_c \) (Fig. 2-A,B) has to be ascribed to an elongation of the droplet as it is transported along the main channel (Fig. 4-H). It is noteworthy that such elongation takes place when the shear forces appear to be quite consistent, and noticeably in the emergence of the jetting regime. Apart from this elongation, the droplet produc-
tion in shear thinning continuous phases is qualitatively similar to that occurring in purely Newtonian systems. A quantitative comparison between Newtonian and non-Newtonian systems is then performed for selected values of the viscosity ratio \( \lambda \), and of the flow-rate ratio \( \varphi \).

In the left column of Fig. 3 the average normalized droplet length \( L/W \) is reported as a function of the con-

FIG. 1: Snapshots of droplets generation at the microfluidic T-Junction. Snapshot (A): the two inlets of the T-junction have the same width \( W \) and the same height \( H \) (not shown); the dispersed phase enters in the junction from the top with flow-rate \( Q_d \), the continuous phase enters from the left side with flow-rate \( Q_c \). The length \( L \) of the droplets is measured by real time image processing while they cross a rectangular window (the dashed contour) positioned downstream of the T-Junction. Left snapshots (A-E) report a breakup occurring in Newtonian continuous phase (N3 is shown, see Table I for details), right snapshots (F-J) report breakup occurring in a shear thinning continuous phase (Xanthan 400 ppm is shown, see Table II for details). Droplets are formed in squeezing (A, J) dripping (C, H) or jetting (E, J) regimes. Snapshots (B,G) and (D,I) outline the emergent dripping and jetting regime respectively.
FIG. 2: Normalized, dimensionless length $L/W$ of the droplets formed at the microfluidic T-junction as a function of either the flow-rate of the continuous phase $Q_c$ (top axis of panels (A-E), bottom axis of panels (G-I)) or the corresponding Capillary number $Ca$ (bottom axis in panels (A)-(E)) for different values of the flow-rate ratio $\phi$, indicated by different symbols according to the legend reported in Panel (F). Panels (A-E) refer to the Newtonian fluids listed in Table I, while Panels (G-I) correspond to the polymers listed in Table II. Open circles mark the flow-rate $Q^*_c$ corresponding to the onset of the jetting regime, accordingly to the maps shown in Fig. S1 of the ESI.

Data. With such rescaling, the droplets produced at a given $\phi$ display essentially the same size either they are formed in Newtonian or non-Newtonian, shear thinning, continuous phases. This provides a direct, experimental evidence of the validity of the $Ca$ number to capture the shear distribution inside the microfluidic channel when a shear thinning fluid is flowing at a given $Q_c$. To better understand the role played by the Xanthan solutions, the droplet breakup experiments are complemented with realistic numerical simulations.

IV. NUMERICAL RESULTS

Initially, The LBM simulations are compared to experiments performed with pure Newtonian fluids. Corresponding results are reported in Fig. 4. They display behaviours which quantitatively well compare with the experimental data in the time dynamics of the breakup process. Specifically, in panels (A-H) we report a representative case corresponding to $Ca = 0.0085$, $\phi = 0.4$ and $\lambda = 1.0$, where the system is transiting from the squeezing dominated regime to the dripping regime. The process of droplet formation comes out to be very well
FIG. 3: Experimental (top white panels) and numerical (bottom orange panels) normalized droplet length $L/W$ as a function of the flow-rate of the continuous phase $Q_c$ (left column) and the effective Capillary number $\overline{Ca}$ defined in Eq. 4 (right column), for different values of the flow-rate ratio $\varphi$, which is increasing from top to bottom rows. Open symbols refer to Newtonian fluids, full symbols of the experimental graphs to shear thinning Xanthan solutions at different concentrations, full symbols of the numerical graphs to power-law fluids with different flow behaviour indexes $n$.

aligned in both experiments and numerical simulations. Notice that we have used the characteristic shear time
reported in the left panel of Fig. 3. We remark that exponent. This well echoes the experimental findings the effect is more pronounced at decreasing the thinning be smaller in comparison to the Newtonian case, and the non-Newtonian fluids the droplet size comes out to

\[ \phi \] snapshots (C–D),

\[ \tau_{shear} = W/U_{av} \] as a unit of time. More quantitatively, for a fixed \( \varphi \), the droplet size is a decreasing function of \( \text{Ca} \) (see Panel (I)); moreover, for a fixed \( \text{Ca} \), one reproduces a linear scaling law for the droplet size as a function of \( \varphi \) (see inset). We generically observed that for Capillary numbers \( \text{Ca} \approx O(10^{-2}) \) the droplet size is well in agreement with the experimental results, and only a slight mismatch emerges at higher \( \text{Ca} \) \([38, 59]\), in the jetting regime, which is however not of interest for the present study. Overall, the simulations of Newtonian fluids retain the key relevant outcomes of the experiments, in terms of droplet size behaviour as a function of \( \text{Ca} \) and \( \varphi \). Hence, with respect to the reference Newtonian case, they are good candidates to explore quantitatively the effects induced by the non-Newtonian behaviour as well as the goodness of the rescaling properties at changing both \( \text{Ca} \), \( n \) and \( \varphi \).

To make progress, in Fig. 4 we report on the effect of thinning phases on the droplet size for a fixed flow-rate \( Q_e \). We have reported a representative case with \( Q_e = 1.23 \) lbu (lattice Boltzmann units), viscosity ratio \( \lambda = 1.0 \) and flow-rate ratio \( \varphi = 0.5 \). We consider both Newtonian (\( n = 1 \), snapshots (A–B)) and non-Newtonian (\( n = 0.9 \) snapshots (C–D), \( n = 0.7 \) snapshots (E–F)) cases. For the non-Newtonian fluids the droplet size comes out to be smaller in comparison to the Newtonian case, and the effect is more pronounced at decreasing the thinning exponent. This well echoes the experimental findings reported in the left panel of Fig. 3. We remark that

\[ \text{Ca} \approx 0.0085 \] for different Newtonian continuous phases (fluids N3 and N4 are shown, see Table 2 for details).

\[ \lambda \approx 0.0085 \]

\[ \text{Ca} \approx 0.0085 \]

\[ \varphi \approx 0.4 \]

\[ \lambda \approx 1.0 \] at the microscales of the present experiments, the non-Newtonian LBM contain essentially the same information as the hydrodynamic NS equations supplemented with shear thinning bulk rheology Eq. 1 (see also Section VI of ESI), hence they strongly corroborate the idea that the observed results originate from a combination of hydrodynamics and bulk thinning phases. To further support this idea, we have computed the viscous stress in the continuous phases along a slice located at half of the channel height. This is overlaid on the density contours in Fig. 5. We indeed see that the viscous stress is more intense close to the boundaries at decreasing \( n \). This explains the observed discrepancies in droplet sizes, in that whenever a larger viscous stress is present close to the wall, this results in a smaller droplet size. To complement the results reported in the top (white) panels of Fig. 3 numerical data for the normalized droplet length at changing Ca, \( \varphi \) and \( n \) are reported in the bottom (orange) panels of Fig. 3. The overall picture emerging from Fig. 3 highlights that the proposed rescaling arguments work well for a wide range of thinning fluids (\( n = 0.5 - 1.0 \)) and flow-rate ratios (\( \varphi = 1/40 - 1.0 \)). Overall, whenever weak discrepancies emerge, they are of the same order of magnitude for both experiments and numerical simulations; since numerical simulations are performed with purely thinning fluids, it is unlikely to attribute such discrepancies to the weak normal stresses of Xanthan \([30, 31]\).
FIG. 5: Snapshots of droplet formation process in numerical simulations with LBM, reporting two representative situations before (left column) and after (right column) the breakup process has occurred. 3D snapshots are overlaid on the viscous stress in the continuous phases computed along a slice located at half of the channel height. The flow-rate ratio is kept fixed to $\varphi = 0.5$ and the flow-rate in the continuous phase to $Q_c = 1.23$ lbu. Different power-law exponents are used: Newtonian fluid ($n = 1$, snapshots (A-B)), thinning fluid with thinning exponent $n = 0.9$ (snapshots (C-D)) and $n = 0.75$ (snapshots (E-F)).

V. CONCLUSIONS

We have extensively studied the droplets breakup in a microfluidic T-junction driven by either Newtonian or non-Newtonian (shear thinning) continuous phases. We have measured the droplets size over a wide range of the viscosity ratio $\lambda$ and flow-rate ratio $\varphi$ still partly unexplored [35] [44] [55]. Squeezing, dripping and jetting regimes are identified for Newtonian and non-Newtonian continuous phases and the resulting breakup maps look quite similar. The droplet length in the squeezing and dripping regimes is found to nicely scale with an effective Capillary number, which reduces to the usual Capillary number when the fluid is Newtonian. The experiments are complemented with numerical simulations based on lattice Boltzmann models (LBM) with purely thinning fluids. The simulations show that for the same injection flow-rate, the viscous stress is more intense close to the microchannel walls for a shear-thinning fluid, thus yielding smaller droplets as observed in the experiments. The rescaling with the effective Capillary number is also verified in numerical simulations, thus confirming that the observed properties are solely ascribed to a combination of continuum hydrodynamics and purely thinning phases. Our results provide new insights into the formation and the manipulation of droplets in the presence of non-Newtonian confined environments and show that LBM can be successfully employed for the simulation of such complex microfluidic systems. Measurements are currently in progress on the generation of oil droplets in polyacrylamide (PAA) solutions [60, 61] characterized by strong elastic effects, while showing only weak shear thinning properties.

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