

Experimental investigation of liquid ligament fragmentation

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Abstract

In this work the stretching dynamics and break-up mechanisms of suspension ligaments are investigated experimentally. A device is designed and presented which creates a ligament by rapid elongation of a liquid bridge and allowing it to stretch at a precisely adjusted, constant rate of acceleration. The experiments are performed with pure Newtonian liquids and suspensions of spherical glass particles (3-20 μm) in water with mass fractions up to 0.8. The bridge thinning and ligament break-up process is recorded using a high-speed camera system.

Introduction

Fragmentation of stretched liquid ligaments is a phenomenon which is observable in various industrial applications. For example in roll coating or printing machines, when ink films split between rollers, ligaments form when cavitation bubbles are created by the low pressure on the exit side of the rollers. Such filaments are rapidly stretched due to high printing speeds and break up into tiny unwanted droplets, which lead to the misting problem [1]. Furthermore, fragmentation is one of the fundamental processes in spray generation since atomization of a liquid surface often implies the formation of liquid ligaments which erupt from the surface, elongate and break up into single droplets [2]. Similar processes are used for estimation of the rheological properties of non-Newtonian liquids [3].

Prevention of misting and controlling droplet size distributions in spray atomization requires a fundamental understanding of the process of liquid ligament fragmentation. Progress on this topic can be achieved by focusing on single liquid ligaments instead of the total process, whereby a device is required to create them. One way of producing a single liquid ligament was published in [2]. A glass tube is placed vertically so that its lower end dips slightly under the surface of a liquid reservoir. The tube is then manually pulled upward and a liquid thread is created during breakup. Newtonian fluids with viscosities up to 20 mPas were tested and it was found that slow pulling led to a single droplet, while fast pulling created long filaments which broke up and produced droplets of various sizes.

A much wider range of fluids, especially non-Newtonian fluids with the characteristics of paper coatings have been investigated in [1]. The aim of this work was to clarify how fluid properties affect misting. A device was designed which creates a filament by elongating a liquid bridge and stretches the filament at a high and constant rate of acceleration, to mimic coating machine kinetics. The plate movement was realized by heavy-duty industrial springs, which do not allow a precisely controllable and reproducible adjustment of the acceleration rate.

The main subject of the present work is to design an experimental setup which allows the investigation of liquid bridge stretching and ligament break-up under controllable and adjustable conditions.

Experimental Methods

Experimental Setup

In order to produce single liquid ligaments a special device is designed, which is shown schematically in Fig. 1. A liquid bridge, which is initially formed between two parallel plates, is stretched by moving the plates apart from each other. The apparatus consists of the following main components: two fixtures for the plates, a linear drive system, a displacement pipette for liquid metering, and two high-speed camera systems including lighting. The setup is built in such a way that the top plate is mounted at a fixed position while the upper one is connected with the linear drive system in order to achieve the maximal possible acceleration downwards. The plates are aligned perfectly parallel to each other. A displacement pipette was used for metering, which allows dosing both low viscous and highly viscous liquids. The adjustable volumes range from $V = 0.5 \mu\text{l}$ up to $10 \mu\text{l}$.

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The first camera is positioned horizontal to the gap and records the stretching and break-up processes, while the second one is positioned above the upper plate in order to record any motion of the contact line during the experiments, since the contact line is free to move.

The motion of the movable plate is accurately controlled by the linear drive system. It operates with a positioning accuracy of 5 μm , while the speed is adjustable in the range of $v = 0.1 \text{ mm/s}$ up to 4 m/s with a maximal achievable acceleration of $a_{\text{max}} = 200 \text{ m/s}^2$. The selected motor enables a variety of different plate motions and their influence on liquid bridge stretching and break up to be studied. Furthermore, it is possible to reduce the initial gap between the two plates down to 10 μm , whereby one can investigate film splitting as it occurs, for example, in printing processes.

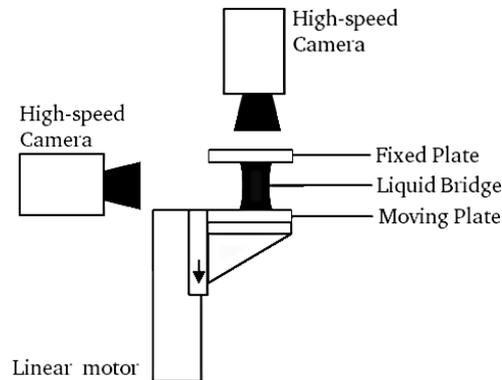


Figure 1 Experimental setup for liquid ligament production.

Materials

Experiments were performed with mixtures of glycerine and de-ionized water as well as suspensions of soda-lime glass beads in de-ionized water at various concentrations. The density of the glass material is $\rho_g = 2500 \text{ kg/m}^3$, the particle sizes range between $d_g = 3 - 20 \text{ }\mu\text{m}$. The surface tension of the different fluids was determined using a bubble pressure tensiometer. The variation of surface tension is less than 10% of the surface tension of water for all fluids used in the experiments.

The shear viscosity of the glycerine and water mixtures and suspensions has been measured by use of a HAAK rotational viscometer in the plate-plate configuration for shear rates between $\gamma = 50$ and 500 1/s. For a mass fraction of 40% particles, which is one of the suspension concentrations used in this investigation, the shear viscosity is constant at a value of $\mu_{p_{40}} = 4 \text{ mPas}$ over the applied shear rate. For higher particle concentration of 60% wt., the shear viscosity reduces slightly to between $\mu_{p_{60}} = 32$ and 24 mPas, as can be seen in Fig. 2. The measured shear viscosity of 75% wt. glycerine and 25% wt. water mixture is about $\mu_{g_{75}} = 24 \text{ mPas}$.

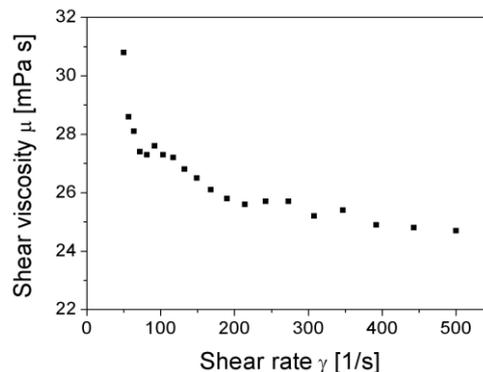


Figure 2 Shear viscosity of the 60% dense suspension.

Experimental procedure and data evaluation

The experimental procedure is as follows. By using a displacement pipette a defined amount of liquid is deposited onto the movable plate which approaches the fixed plate until a liquid bridge is formed in the gap between the plates. A ligament is created stretching the bridge uniaxially by then driving the movable plate apart from the fixed plate.

Plate motion always starts from rest, which means an acceleration phase is present until a constant velocity is reached. If a very low plate velocity of for example $v = 1 \text{ mm/s}$ is required, minimal acceleration times of the order of one-tenth of a millisecond are achievable. For larger velocities like $v = 1000 \text{ mm/s}$ the acceleration time increases up to more than one millisecond before the change in the plate movement from a constant acceleration to a constant velocity occurs. All experiments were performed using constant plate acceleration, varied between $a = 10 \text{ m/s}^2$ and 150 m/s^2 .

The mid-point diameter of the stretched liquid bridge over time, the height of the bridge over time, the ligament breaking length, the numbers of droplets as well as the size of droplets were determined using the image processing of the captured video sequences.

Results and Discussion

Observations

Figure 3 and 4 show exemplary the process of liquid ligament generation, detachment and breakup for various acceleration rates and particle concentrations. In all cases the acceleration was constant during the entire image sequences.

In Fig. 3 a liquid bridge of the volume $V = 3 \mu\text{l}$ of pure de-ionized water is stretched at a constant acceleration of $a = 50 \text{ m/s}^2$. When the movement of the lower plate starts, the bridge radius at the middle starts to contract, as it can be seen 4 ms after the beginning of the process. The contact lines of the bridge recede neither on the fixed nor on the translated plate. At this low rate of acceleration the ligament breaks up at its extremities at nearly the same instant of time. The free ligament forms a single droplet in less than one millisecond.

The stretching and break-up process for water, but at a higher constant rate of acceleration, $a = 150 \text{ m/s}^2$, is shown in Fig. 4 (a). The higher acceleration rate leads to a more rapid stretching of the liquid bridge, as can be seen in the image of the time step 4 ms, where the height of the bridge is much larger than at the same time step for the slower acceleration. When the extension is rapid compared to the initial capillary time, the central part of bridge takes the shape of a liquid column. The detachment of a free ligament occurs in a different manner than in the first case. The ligament first breaks up at the top plate and, after a time interval of $\Delta t = 1.28 \text{ ms}$, at the bottom plate. After detachment the behaviour of the ligament is comparable to that of a free jet. Tiny undulations grow on the jet. Since the free ligament is long enough those undulations later grow large enough to break the jet into two droplets as can be seen in the last image of this sequence.

The image sequences shown in Fig. 4 (b) and (c) demonstrate the influence of particles on ligament stretching and breakup. In both sequences the acceleration is $a = 150 \text{ m/s}^2$. From the rheological measurements it is known that increasing the particle concentration leads to an increase of the shear viscosity of the suspension and non-Newtonian flow behaviour. At a particle concentration of 40 % wt., the shear viscosity is about $\mu_{p,40} = 4 \text{ mPa s}$ and independent of the shear rate. The process of liquid bridge stretching and break-up looks in principle similar to the case of water at the same acceleration. One observable difference is that the time until the ligament breaks up at the top, as well as the time between the first and second breakup, increases in comparison to pure water. The larger viscous stresses delay the pinch-off and break-up of the ligament; it took longer for constant capillary forces to overcome the increasingly larger viscous forces. Additionally the ligament length increases for the higher viscosity, while its diameter decreases. The development and growth of the undulations on the free liquid ligament are also dampened by the higher viscosity. Nevertheless the longer length of the ligament finally leads to the production of multiple droplets as is shown in the last image of this sequence.

A further increasing of particle concentration up to 60% wt. leads to an enhancement of the described effects as can be seen in Fig. 4 (c). The time until the ligament breaks up at the top takes longer for the higher concentration. The ligament length becomes longer, while the ligament diameter becomes smaller, which leads to a faster fragmentation of the ligament than in the case of lower particle concentration or pure water.

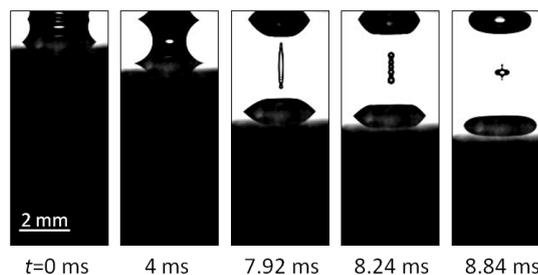


Figure 3 Stretching and break-up of a water liquid bridge of volume $V = 3 \mu\text{l}$ at a low rate of acceleration of $a = 50 \text{ m/s}^2$

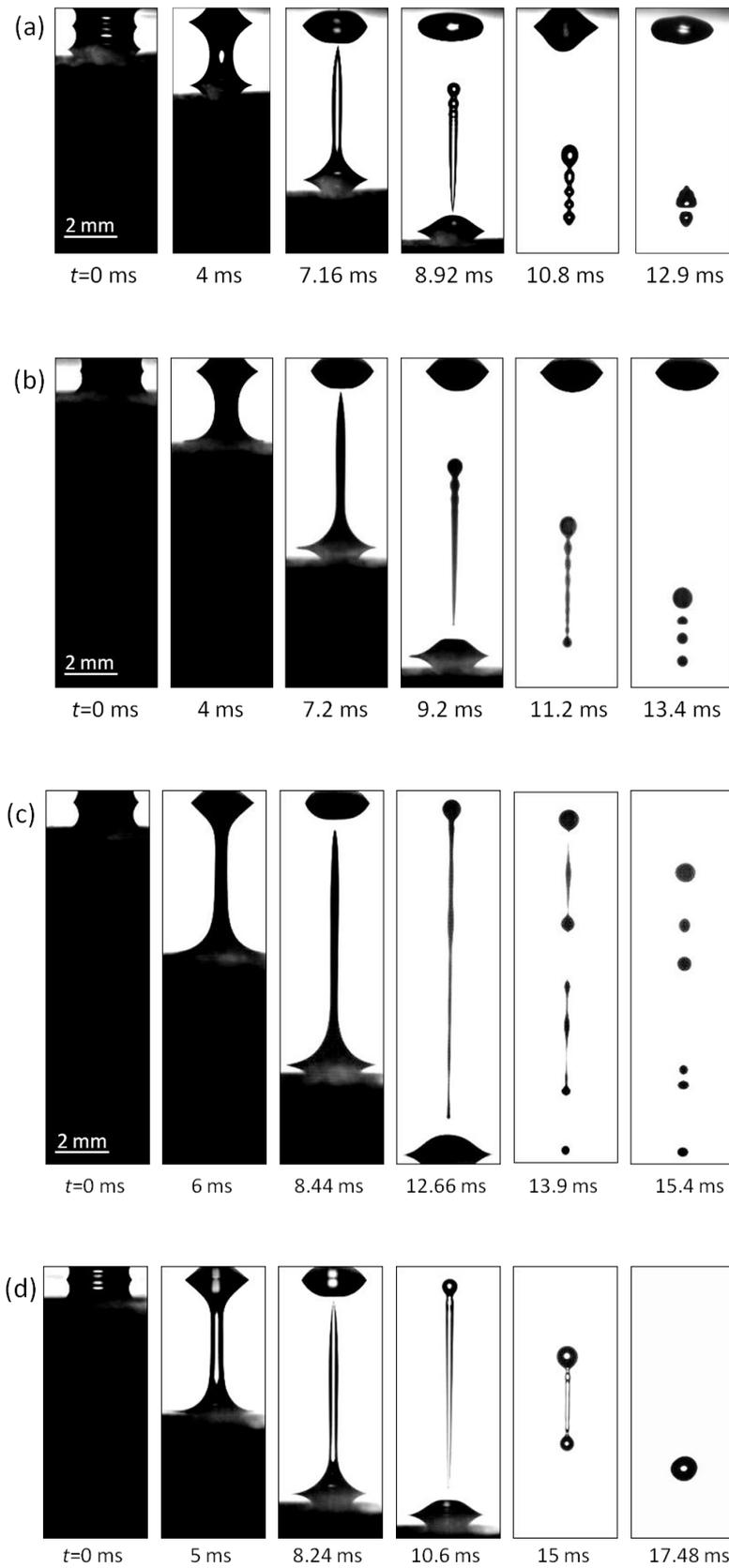


Figure 4 Stretching and fragmentation process for various fluids of volume $V = 3\mu\text{l}$ at constant acceleration of $a = 150 \text{ m/s}^2$. (a) Pure Water, (b) 40% wt. particles, (c) 60% wt. particles and (d) 75% wt. glycerin.

The stretching and fragmentation process of a liquid bridge of 75% wt. glycerine mixture, shown in Fig. 4 (d), differs enormously from that of the dense suspension, although both have a comparable shear viscosity. After a single ligament has detached from the liquid bridge, two blobs are formed at its edges. They propagate towards the ligament center. Neither the growth of undulations on the ligament, nor its fragmentation into multiple drops is observed.

Figures 3 and 4 reveal that the total process, beginning from the state of a liquid bridge to the formation of satellite drops, can be subdivided into three phases for every fluid used in this work. The first phase is the contraction of the middle diameter of the liquid bridge, when the upper plate starts to move downward. The second is the detachment of the stretched ligament at its extremities; the third phase is the contraction of the free ligament and its fragmentation into one or more satellite droplets. In order to investigate these three phases in more detail, different measurements were obtained from the image processing of the images.

Stretching of the liquid bridge

At the beginning of the stretching processes, the increase of the liquid bridge height is accompanied by a reduction of the liquid bridge radius. In order to investigate the rate of contraction in dependency of different influencing factors, the diameter in the mid-point of the bridge has been determined from the images. Figure 5 (a) shows the evolution of this diameter until the first breakup for a liquid bridge of water at four different acceleration rates. In Fig. 5 (b) the same diameter is shown as a function of the dimensionless gap length h/D_{mid} . Since the initial height of the liquid bridge varies slightly in the experiments, the diameter has been normalized by the mid-point diameter at time $t = 0$ s, which varied between $D_{\text{mid}}(t=0) = 1.8\text{-}2.01$ mm. During the first 1.5 milliseconds all curves display the same slope, which indicates that the shape of the bridge is nearly static, determined exclusively by the geometry, since the inertial and viscous stresses in the liquid are small in comparison with the interfacial stresses.

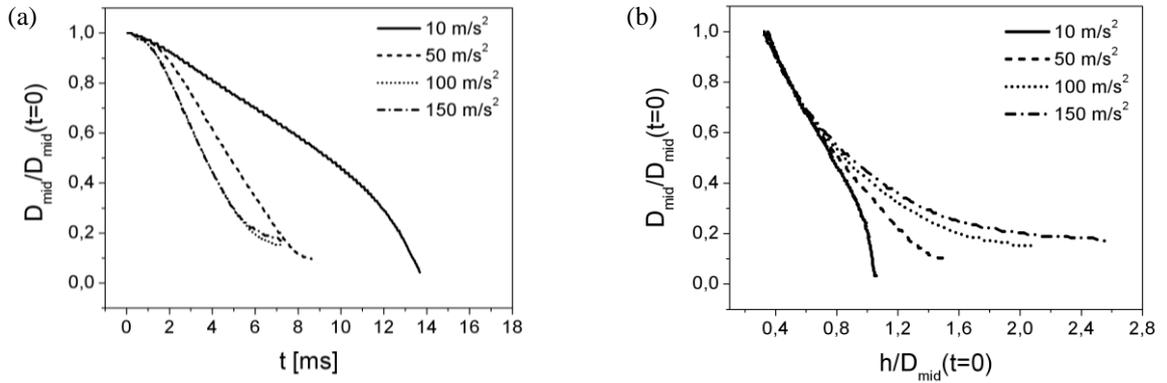


Figure 5 (a) Evolution of the mid-point diameter D_{mid} of a water liquid bridge over time for different acceleration rates. (b) Evolution of D_{mid} of a water liquid bridge over liquid bridge height for different acceleration rates.

As shown in Fig. 5 (a) the diameter D_{mid} decreases in time almost linearly. This linear reduction of the liquid bridge diameter in time contradicts the predictions [2] that the diameter of the ligament reduces as $D_{\text{mid}} \sim t^{2/3}$. One can assume that this process is similar to the jet behaviour during rheological tests. In such cases that rate of the diameter reduction of time is $\sigma/(3\mu)$, which is much higher than the rates observed in our experiments.

The slope of the curves increases for relatively small plate accelerations (less than $a = 100$ m/s²) and its value saturates at high accelerations. The curves for $a > 100$ m/s² almost coincide. To explain this phenomenon the local velocity of the plate is compared with the characteristic velocity of propagation of the capillary wave along the liquid bridge, $v_{\sigma} \sim (\sigma/(\rho D_{\text{mid}}))^{1/2}$. The comparison is shown in Fig. 6 for the accelerations $a = 50$ and 100 m/s². In the case of $a = 50$ m/s² the plate velocity is smaller than v_{σ} during the entire process and the dynamics of the liquid bridge stretching is influenced by the plate motion. At higher acceleration, Fig. 6 (b), the plate velocity exceeds v_{σ} at $t = 2$ milliseconds. This means that at larger times the information about the plate motion does not reach the remote regions of the bridge, and its dynamics is not longer influenced by the plate acceleration.

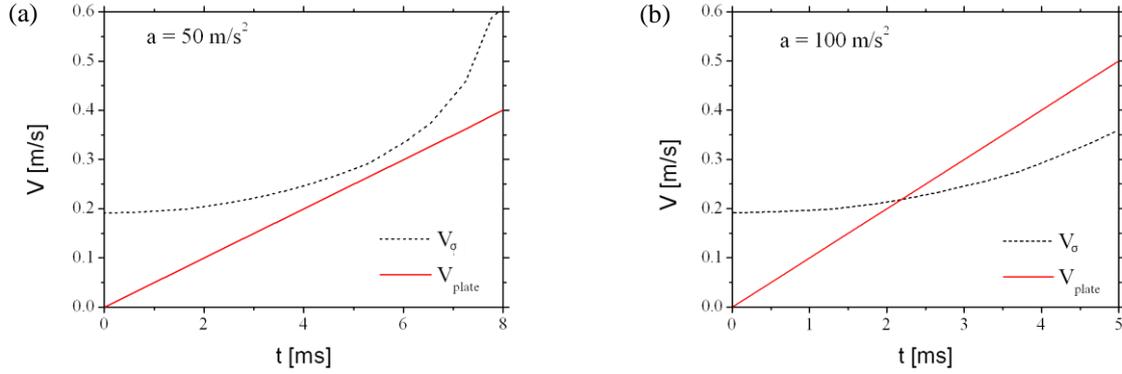


Figure 6 Comparison of the plate velocity, V_{plate} , with the velocity of propagation of the capillary wave, V_{σ} .

Near the end of the stretching phase the contraction behaviour seems to differ for the different acceleration rates. At an acceleration rate of $a = 10 \text{ m/s}^2$ the contraction of the diameter increases at the end, while it decreases for higher acceleration rates. The change in the slope of the curve indicates the beginning of the ligament detachment, as it will be explained in the next section.

By plotting the same diameters against the dimensionless gap length h/D_{mid} of the liquid bridge instead of process time, one can see that at the beginning of contraction the diameter of the liquid bridge depends on its height and not on the time to reach the height, Fig. 5 (b). This result indicates that the form of the liquid bridge can be approximated well by the static shape, whose analytical solution is known [4]. For a given liquid volume the static solution exists only for a finite range of the bridge lengths.

In the diagrams in Fig. 7 the evolution of the mid-point diameters of the different liquids used in the experiments are compared for different plate accelerations. No significant difference in the curves is noticeable for an acceleration of $a = 10 \text{ m/s}^2$ as well as for a higher acceleration of $a = 150 \text{ m/s}^2$. From that it can be concluded, that inertial forces govern this flow.

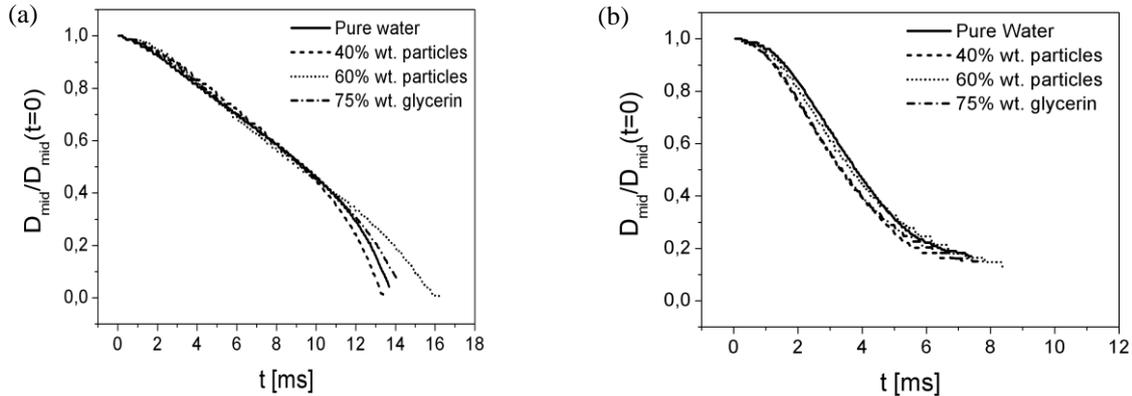


Figure 7 Evolution of the mid-point diameter D_{mid} of liquid bridges over time for various fluids at different acceleration rates. (a) Acceleration rate $a = 10 \text{ m/s}^2$, (b) $a = 150 \text{ m/s}^2$.

Detachment of liquid ligament

In the previous section it was pointed out, that the change in the evolution of the liquid bridge mid-point diameter just prior to breakup is different for low and high acceleration rates. While the contraction increases near the breakup for low accelerations it decreases for higher accelerations. Figure 8 helps explain this difference. In both images the mid-point diameter D_{mid} and minimum diameter D_{min} of the liquid bridge, as well as the position of the minimum diameter $z(D_{\text{min}})$ have been plotted versus time of the stretching processes. The position of the minimum diameter is described in coordinate systems which origin lies in the mid-point of the liquid bridge and which vertical axes z is counted positive in the direction of the plate movement. Furthermore the position has been normalized by half the height of the liquid bridge at every step of time. In the left image the results at a low acceleration of $a = 10 \text{ m/s}^2$ are shown. The evolution of the mid-point and minimum diameter is nearly identical. When the liquid ligament is slowly extended, the bridge has time to adjust its shape to reach a stable equilibrium at each instant of time. Above a critical height no stable equilibrium exists and the bridge quickly contracts, which can be seen in the increase of contraction near the break-up of the bridge.

Figure 8 (b) shows the case of a high acceleration. The minimum diameter follows the mid-point diameter during the first 4 ms of stretching. After that the curve of the position of the minimum diameter is no longer zero but starts to grow. The position of the minimum diameter is changing from the middle of the bridge towards the upper extremity. The detachment of the ligament begins and from that time on its diameter stays nearly constant.

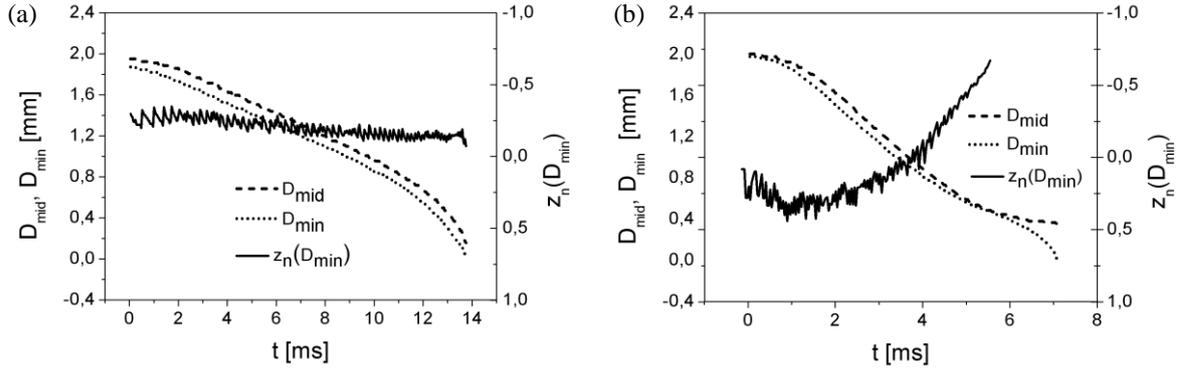


Figure 8 Axial position of the neck $z_n(D_{\min})$, corresponding to the minimum ligament diameter D_{\min} , for two different accelerations. (a) $a = 10 \text{ m/s}^2$, (b) $a = 150 \text{ m/s}^2$.

While the contraction of a liquid bridge during stretching was similar for the different fluids, large differences were observable during the detachment of a ligament from the middle of the stretched bridge. The ligament first break-up at the top extremity, as it can be clearly seen in Fig. 4. The time of the first break-up t_{Bbr} depends on the acceleration rate and liquid properties. Higher accelerations lead to a decrease of the first break-up event, while a higher particle concentration or viscosity delays the break-up, Fig. 9.

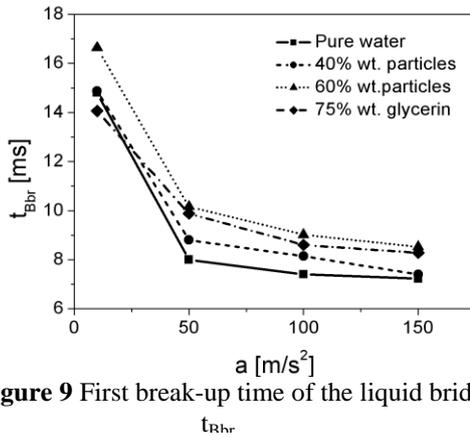


Figure 9 First break-up time of the liquid bridge, t_{Bbr}

The total axial force applied to the ligament center consist of surface tension, $\sigma \pi D$, and the force associated with the capillary pressure, $p_c \pi D^2$, where $p_c = 2 \sigma/D$, is the Young-Laplace pressure. The total force is $\sigma \pi D/2$. This force is balanced by the inertia of the liquid entering the blob: $\rho U^2 \pi D^2/4$. The momentum balance yields the following expression for the velocity U of each blob relative to the ligament:

$$U = (2\sigma/(\rho D))^{1/2}$$

The lifetime of the ligament is therefore $L/(2U)$, where L is the initial ligament length. The results of the measurements of the ligament lifetimes for various liquids are shown in Fig. 10 and compared with the theoretical prediction. The agreement is rather good. Some minor underestimation of the time is explained by the ligament stretching, which is not accounted for in this estimation.

Fragmentation

After the first break-up the stretching of the ligament continues. Therefore ligaments of longer length are obtained at higher plate accelerations as is shown in Fig. 10 (a). For pure water as well as the suspension of 40% wt. particles the increase in the length is linear with an increase of the acceleration, while for the higher suspension at acceleration for $a = 150 \text{ m/s}^2$ the increment in length becomes much higher.

As soon as the free ligament is detached from the liquid bridge, two blobs are formed at its edges, which can be seen clearly in Fig. 4 (b). They propagate towards the ligament center. This motion is governed by inertial and capillary forces. The

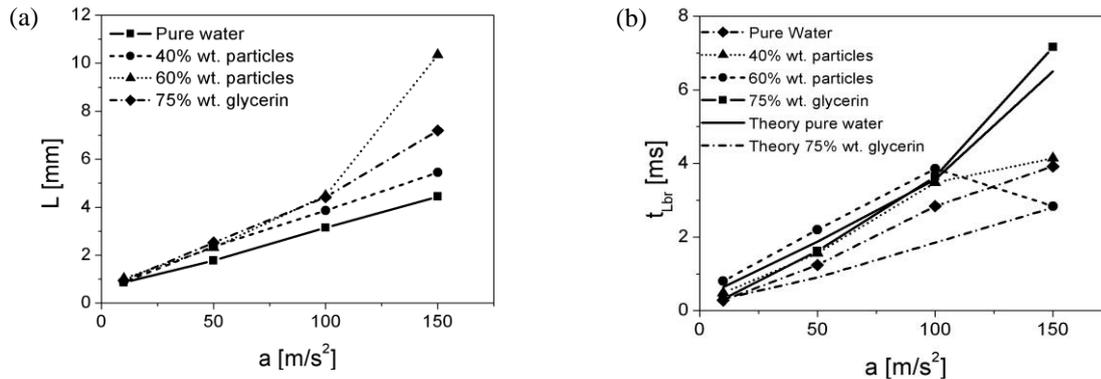


Figure 10 (a) Length of the detached liquid ligament L and (b) lifetime of a free ligament t_{Lbr} .

Finally, the number of drops formed after the ligament breakup is shown in Fig. 11. It is interesting that the number of drops monotonically increases with the stretching acceleration. This result is not surprising, since higher acceleration leads to longer ligaments. It is important to note, that the breakup of the ligament into two or more drops is determined by the competition of two times: the duration of the blobs propagation and the time of breakup due to the Rayleigh capillary instability.

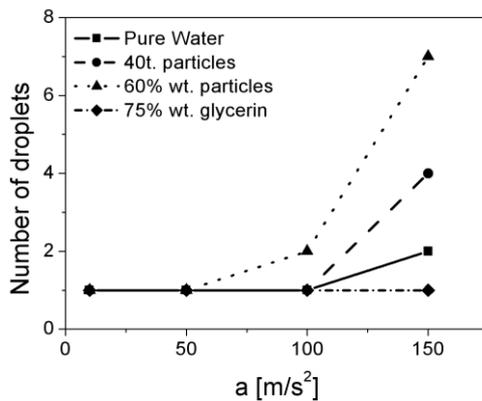


Figure 11 Number of drops formed after the ligament break-up.

Conclusions

In this paper the filament stretching with constant acceleration is investigated experimentally. This case is associated with the technology of offset printing. It was shown that the evolution of the ligament diameter only slightly depends on the liquid properties but is significantly influenced by the acceleration. However, the ligament length at the instant of breakup, its lifetime and the number of the resulting drops depend on the surface tension and viscosity. The number of drops increases monotonically with the stretching acceleration and with the concentration of the suspension.

The theoretical estimation of the rate of propagation of the blobs formed at the ligament edges due to capillary forces, and thus the lifetime of the ligament, agree well with the experimental data.

Acknowledgements

The financial support of C.M.W. from the Center of Smart Interfaces (Technische Universität Darmstadt) is appreciated. Furthermore the authors would like to thank Prof. Edgar Dörsam and Dr. Hans-Martin Sauer from the Institute for Printing Science Technology at the TU Darmstadt for his encouraging discussions about the application of these investigations.

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