LIVING SYSTEMS RESEARCH

Rayleigh-Plateau-like Instability in the Rim Break-Up of a Pulsating Drop

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Abstract. *We investigate the dynamics of a dichloromethane (DCM) adrop placed on the surface of an aqueous solution of cetyltrimethylammonium bromide (CTAB). By varying the CTAB concentration we observe a rich variety of different drop shapes ranging from pulsating over rotating to polygonal-like shaped drops. In the pulsating regime the drop is expanding and retracting in a periodic manner. These pulsations are accompanied by a very regular ejection of smaller droplets, which happens at the end of the expansion of the drop before it retracts again. These droplets are formed from the break-up of an almost perfectly expanding rim that is forming close to the drops maximum expansion. This rim break-up resembles to what is known as the Rayleigh-Plateau instability while in our case several additional features are present in the system. A detailed study indicates that the characteristic wavelength is connected to another instability that occurs on the drop before the rim was even formed. These other instability seems to be of the Benard-Maragoni type leading to a pre-structuration of the drop due to the evaporation of the DCM itself [1]. By theoretical modeling this type of rim break-up in also taking into account the particularities of the system we were able to obtain the experimentally observed values.*

Background

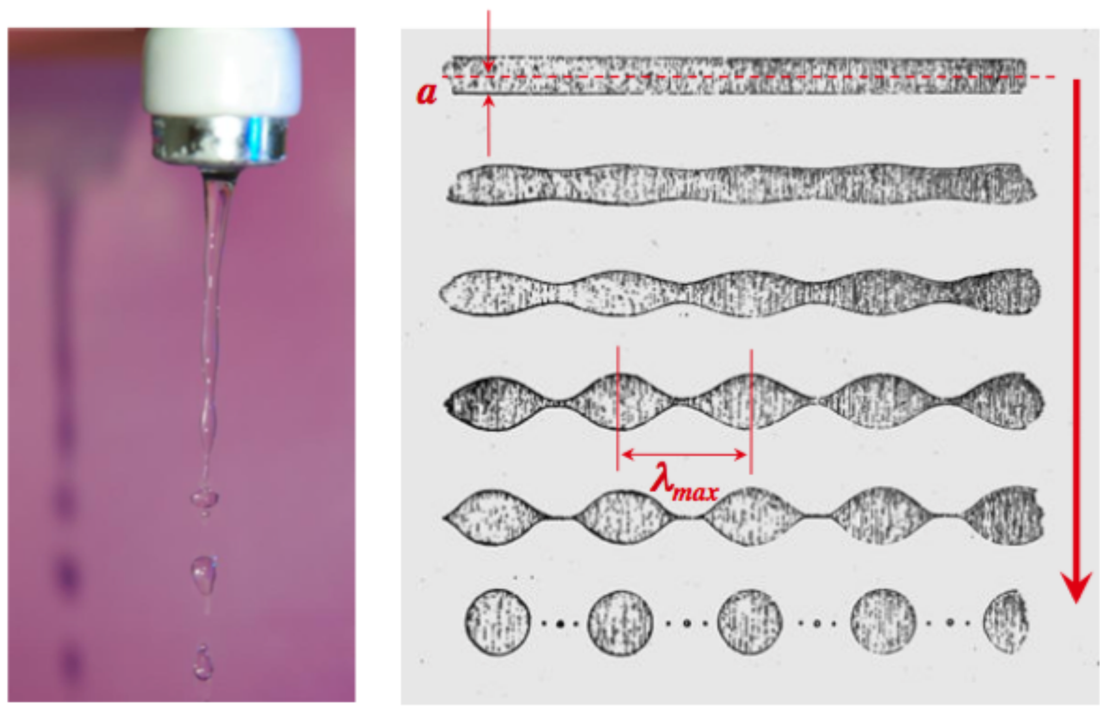


Fig. 2: Rayleigh-Plateau instability. a: Break-up of a water jet from a tab. b: Charakteristic features of this instability.

The Rayleigh-Plateau instabilty (RP) was discovered by Plateau and further investigated theoretically by Lord Rayleigh. It is observed for a liquid column, as for example for a liquid jet from a tap. Random initial fluctuations of the surface of the column are more and more amplified, and the column progressively gets modulated and eventually breaks up into droplets (see Fig. 2). The characteristic parameters of this instability are the *initial unperturbed radius* of the column ***a*** and the *characteristic (maximum) wavelength* of the perturbation $\boldsymbol{\lambda_{max}}$.

Rayleigh found a relation between the initial unperturbed radius and the characteristic wavelength by using a linear stability analysis of the interface, which reads

$$\lambda_{max} = 9.02\, a$$

Experimental Findings

The work presented here is concerned with the rim break-up in the pulsating regime where we observe a RP-like rim break-up. In contrast to the standard RP instability the rim is circular and expanding during the break-up and also stays always connected to the drop almost until the time until it breaks up (Fig. 1). Additionally we have the formation of periodic structures inside the drop (Fig. 3).

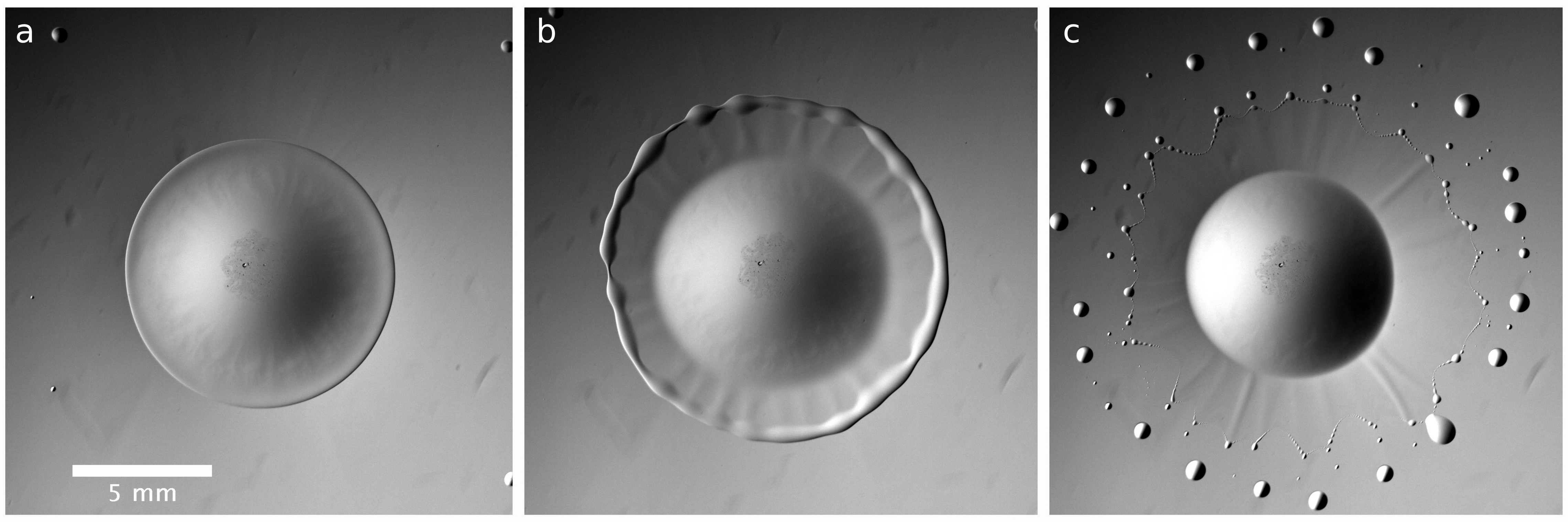


Fig. 1: Expansion of the drop and formation of the toroidal rim that breaks-up into smaller droplets. a: First visible appearance of the rim. b: Rim just before the break-up. c: Shortly after rim break-up, when the connecting film is receding, ejecting smaller droplets at its perimeter.

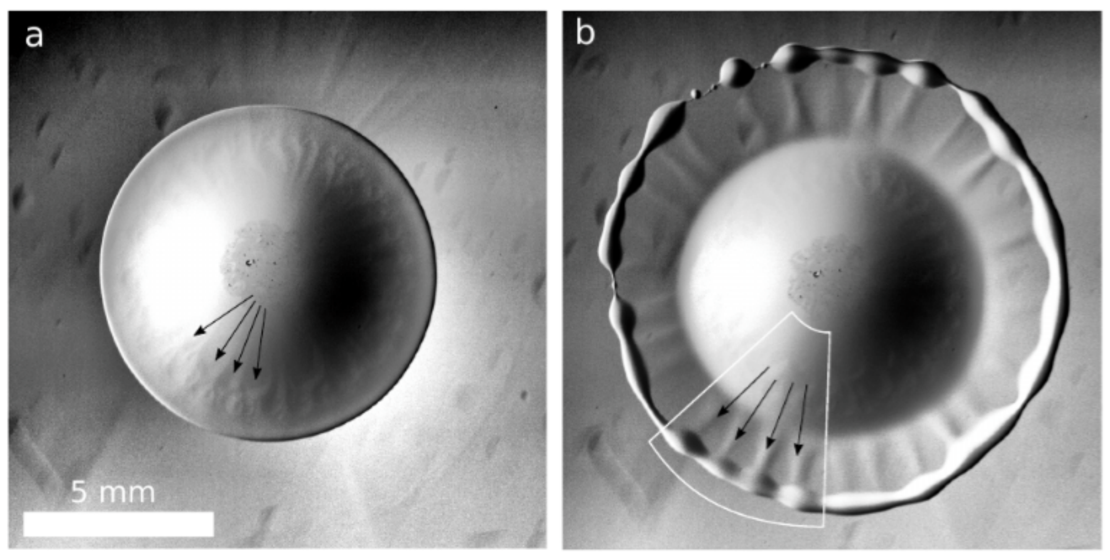


Fig. 3: Periodic structuration inside the DCM drop. a: Structuration at the time when the rim is starting to form. b: Drop at the time just before the rim starts to break-up.

These additional features seem to be also the reason why the characteristic wavelength (i.e. the distance between the ejected droplets) is different from the one expected theoretically (Fig. 4).

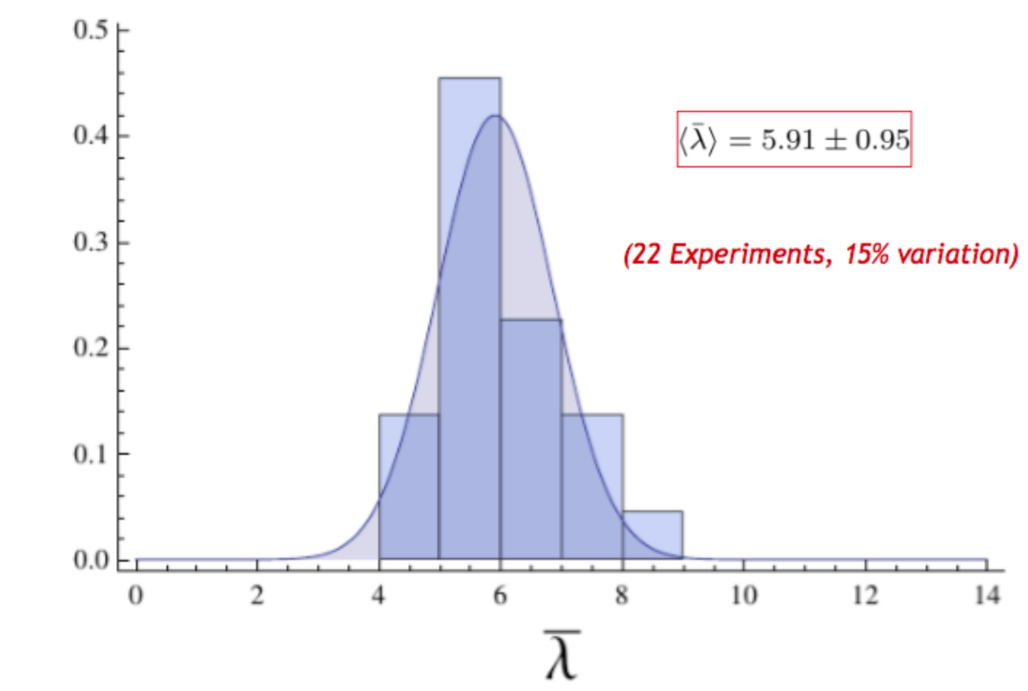


Fig. 4: Observed characteristic reduced wavenlength. Inset: averaged value over 22 experiments.

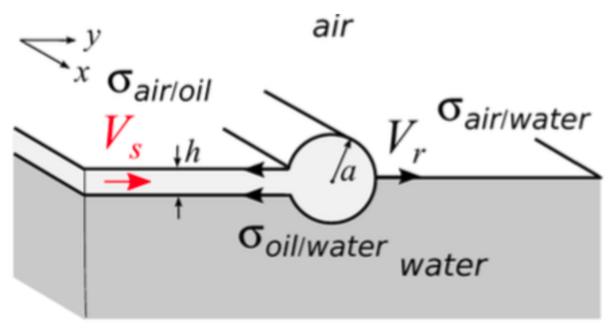
Modeling

The main difference between a standard RP instability and the instability we have in our system is the expansion of the rim and the existence of a film that is connected to the rim.

We use a model proposed by Roisman et al. [1] as a starting point, which we adapted to our situation. For simplifying the problem, we make several assumptions: We neglect the viscosities of oil and water, we neglect the buoyancy effect and assume for simplicity that the cross-section of the rim is circular and only semi-submerged in the water, we assume the film (sheet) to be non-perturbed by the rim evolution and that it remains flat and uniform and we assume only a simple flow inside the rim (no vortex for instance).

With this model we obtain a second solution in respect to the standard RP instability that corresponds to a characteristic reduced wavelength of ***5.72*** which is within the range of what we observe in the experiment.

Fig. 5: Scheme of the model, its parameters and the governing equations.



$$\frac{\partial A}{\partial t} + A_0 \frac{\partial u}{\partial x} - h\,(V_s - V_r) = 0 \quad \text{Mass balance equation}$$

$$\rho_{oil} A_0 \frac{\partial u}{\partial t} - \frac{\partial P}{\partial x} - f_{sx} = 0 \quad \text{Axial momentum}$$

$$\rho_{oil} A_0 \frac{\partial V}{\partial t} - P\kappa - \frac{\partial Q}{\partial x} - f_{sy} = 0 \quad \text{Transvers momentum}$$

$$\rho_{oil} \frac{\partial L}{\partial t} - \frac{\partial M}{\partial x} - Q - m_s = 0 \quad \text{Conservation of Angular Momentum}$$

Conclusions

The described phenomena of a RP-like rim break-up in the pulsating regime of a DCM drop on a liquid surfactant-contaning surface shows some characteristic features not observed in a standard RP instability. Nevertheless an advanced model that takes these pecularities into account the could reproduce the experimental observations accuratly.

References

[1] F. Wodlei, J. Sebilleau, J. Magnaudet and V. Pimienta, Nature Communications Volume 9, Article number: 820, 2018

[2] I. V. Roisman, K. Horvat, and C. Tropea, Physics of Fluids, vol. 18, p. 102104, 2006