The Life of a Free Soap Film

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Motivation and Background

A Brief History: Previous experimental studies exploring the rupture and retraction of soap films have relied on rupture from a point. For example, Lord Rayleigh [1] dropped small metal shot wetted in alcohol through soap films. Ranz [2] as well as McEntee and Mysels [3] punctured films using a localized spark. And Pandit and Davidson [4] and Reyssat and Quere [5] pierced their films with sharp needles and fine wires. Moving beyond this typical technique has been considered impractical as recently remarked in the literature [6]:

"Experimental study of the retraction of a planar film is impractical owing to unavoidable edge effects and the difficulties inherent in producing a perfectly linear rupture."

Motivation: But is it possible to uniformly detach a planar soap film along an edge or its entire perimeter? If this is possible, what happens to this "free" soap film? Answering these basic questions and making the impractical practical was the initial motivation for this research. However, along the way we understood that there are important applications of this technique: e.g. studying along-the-edge instabilities of retracting liquid sheets [7] and properties of Plateau borders, as well as performing gravimetric (non-optical) measurements of average soap film thickness.

Experimental Setup

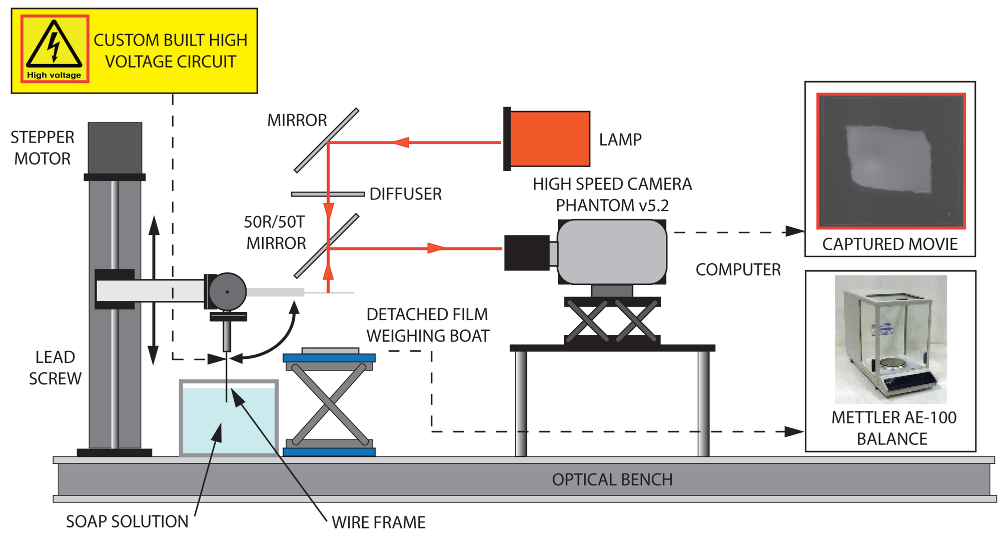


Figure 1: Schematic of experimental setup used for soap film experiments.

- Soap films were formed by withdrawing a wire frame from a bath of soap solution at a constant speed of 2.5 cm/s ($Ca \sim 6.6 \times 10^{-4}$) using a precision stepper motor (Velmex BiSlide). Upon withdrawal, soap films were rotated into a horizontal position to minimize thickness variations across the film. The soap solution was composed of deionized water (18MΩ cm, UCSB Teaching Cleanroom), 4% glycerol (ultra-pure, BP Biomedical), and 0.25 % sodium dodecyl sulfate surfactant (SDS, 99%, Fisher) corresponding to 1 CMC.

Table 1: Properties of Soap Solution

SDS Content	Glycerol Content	Surface Tension	Density	Viscosity
C_{SDS}	C_{Glyc}	σ_{eq}	ρ	μ
$[wt\%]$	$[wt\%]$	$[mN/m]$	$[kg/m^3]$	$[mPa{\cdot}s]$
0.25	4	38	999	1

- The wire frames were made with NiChrome 60 (bare resistance wire, Pelican Wire Co.). Three different wire diameters were used during the course of our experiments (45, 40, and 36 gauge - corresponding to diameters of 44, 79, and 127 μm). The wire frame acts as a resistor connected to a high voltage (HV) circuit, which consists of a large capacitor charged using a Spellman HV power supply and discharged by means of a controlled spark gap. The discharge current passes through the wire frame, which leads to boiling of the soap film immediately in contact with the frame due to Joule heating thereby detaching the film.
- As a result, the soap film retracts from the frame and atomizes yielding small droplets that are collected and weighed with a precision balance having a resolution of 0.1 mg (Mettler AE-100). Reflected and transmitted light was used to image the soap film during its detachment and recorded using a Phantom v5.2 high speed camera.

Ensuring Uniform Detachment of a Soap Film

Visualizing the Detachment: The transition from non-uniform to uniform detachment of a typical soap film is shown in the images of Figure 2 and in the gravimetric data presented in Figure 3.

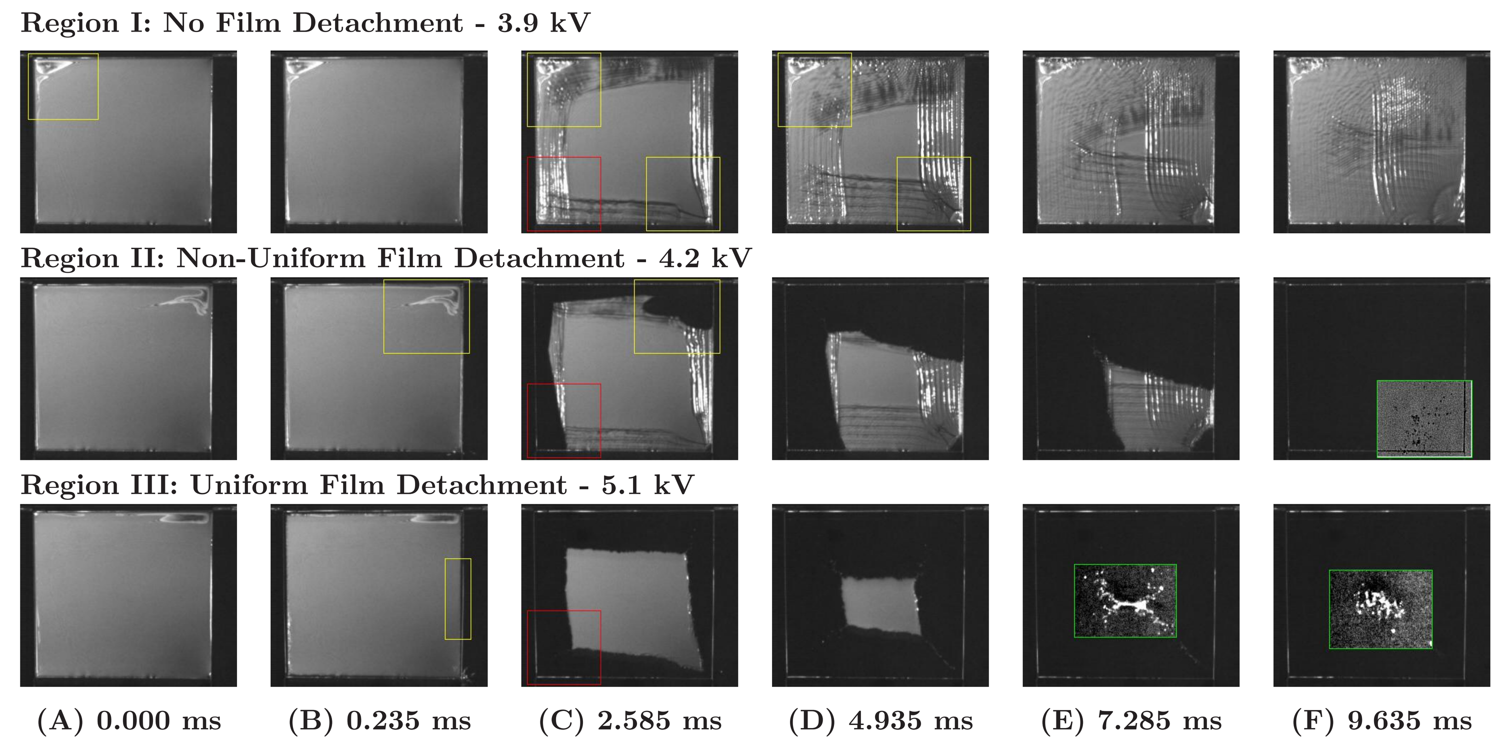


Figure 2: Images from high speed movies recorded of soap films under different retraction regimes. The soap films in these images are 50 mm square.

- The horizontal films have thickness variations due to imperfections in the fabrication and leveling of the frame (a thin spot can be seen as the discoloration highlighted in I-A, cf. Figure 2).
- Region I: Voltages are insufficient to produce film detachment at any point along the wire. Vibration of the wire frame as a result of wire expansion produces waves that propagate through the film. The speed of propagation of these waves varies with film thickness (compare upper left and bottom right corners of I-C and I-D).
- Region II: Voltages cause detachment of the film at multiple locations along the wire frame - but not along the entire perimeter. Often detachment is delayed and waves can be seen to propagate ahead of the retracting edge (II-C,D,F). Thickness variations cause the film to retract with different speeds [8, 9]; compare upper right and bottom left corners of II-C. In region II, a portion of the mass of the film remains attached to the wire as droplets and the outward trajectory of the majority of the mass makes it difficult to collect and measure (note the location highlighted in II-F).
- Region III: Voltages are sufficient to cause uniform release of the soap film (a magnified portion of III-B shows the uniform gap between the released soap film and the wire). The free soap film retracts toward the center where a majority of the film mass is clustered (see the enhanced contrast portion of III-E,F). Gravimetric analysis of soap films utilizes Region III voltages for detachment.

Quantifying the Transition: The three regions visualized in Figure 2 can be quantified in terms of the mass collected during detachment experiments as indicated in Figure 3. Region I is characterized by no film detachment and essentially no mass is collected. Region II is characterized by a sharp rise in the collected mass. Region III exhibits a constant collected mass with increasing applied voltage. The retraction speed of the detached film in region III can be estimated using the Taylor-Culick velocity [8, 9], implying that there exists an immense initial acceleration of the film edge upon detachment.

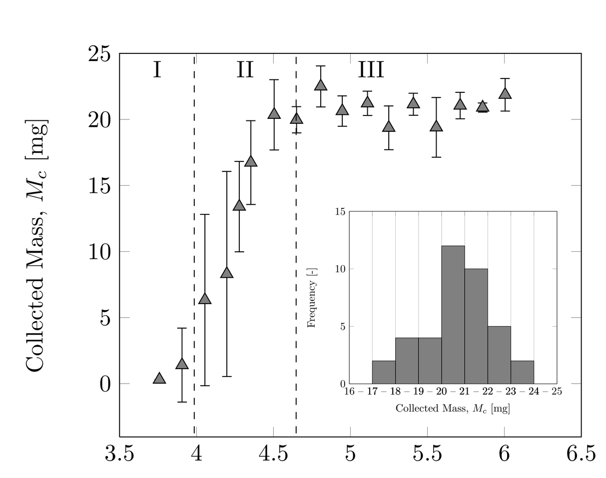


Figure 3: Collected mass of soap films as a function of capacitor voltage for square 40 gauge wire frame.

$$V_{TC} = \sqrt{2\sigma_{eq}/(\rho h_f)} \approx 5\ m/s, \qquad a_{0,film} \approx \sqrt{V_{TC}^2/h_f} \approx 5 \times 10^6\ m/s^2.$$

Gravimetric Analysis of Soap Film Thickness

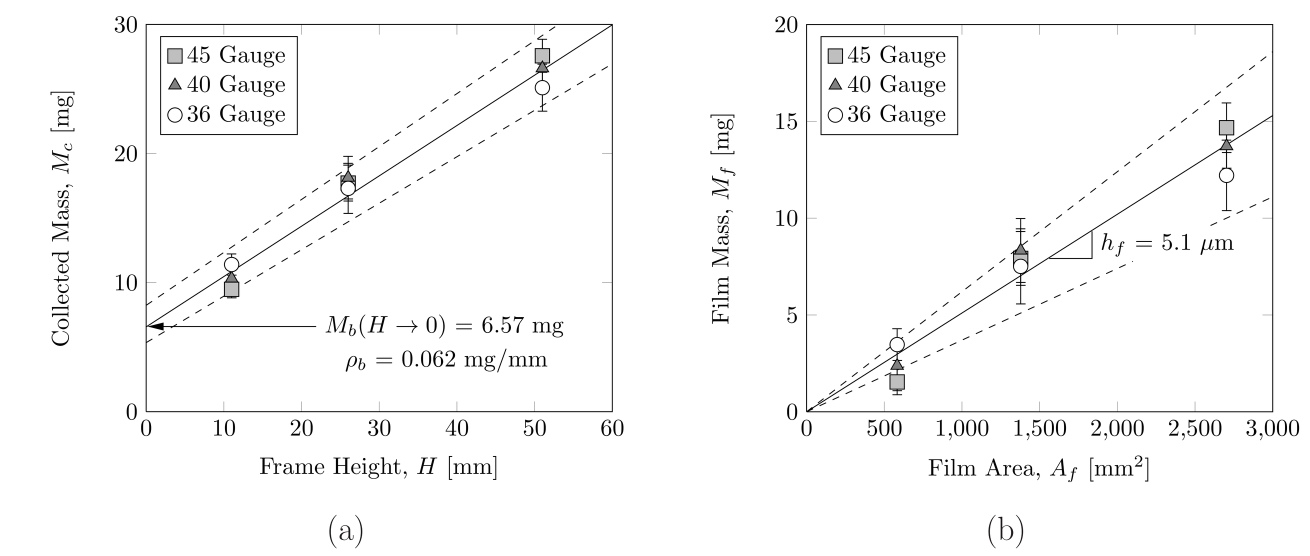
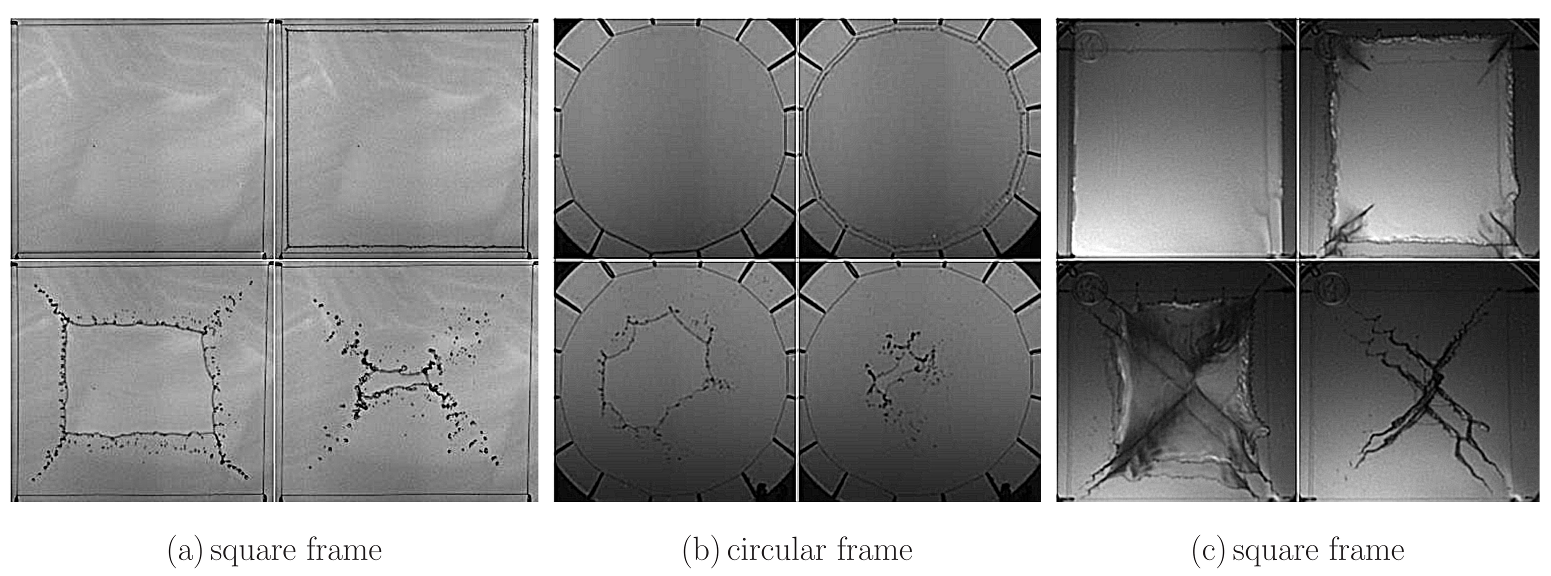


Figure 4: (a) Variation in collected mass with the height of the soap film frame for all three wire diameters tested. The collected mass from all three wire diameters is the same for any particular frame size within the accuracy of our measurements. We can extrapolate the collected mass to a value of zero height using the average mass at each point and the resulting mass will be associated with the Plateau border mass. This border mass can be used to find the Plateau border density, ρ_b. (b) Subtracting the border mass from the collected mass for each frame size yields the mass of the soap film, M_f. As expected, the mass of the film increases with the area of the film in a linear fashion. The slope of the linear fit can be used to find the thickness of the soap films, in this case h_f=5.1 μm. This is consistent with the order of magnitude of film thickness expected based on the fast withdrawal speed, and retraction velocity measurements.

The Life of Free Soap Films - Various Shapes



(a) square frame (b) circular frame (c) square frame

Figure 5: Montage of images demonstrating the uniform release of soap films.

A free soap film lives only within the blink of an eye. Each montage in Figure 5 starts with an image of the undisturbed soap film. Next, the film is seen just after it has been uniformly released from its wire frame. As time progresses the film collapses, and at the end of its life the film disintegrates into small droplets. For the sake of simplicity we began with square frames, cf. Figure 5(a,c), but a more elegant case would be a circular soap film. But how can one create such a film? We tried to do that by increasing the number of eyelets that support the wire frame, cf. Figure 5(b): in this sequence, a soap film frame with 16 eyelets is shown.

Conclusions and Future Work

- We have demonstrated that the uniform detachment of a soap film is possible and characterized the phenomenon gravimetrically.
- Future work includes studying along-the-edge instabilities of liquid sheets and identifying properties of Plateau borders.

Bibliography

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