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High-speed visualization of soap films bursting dynamics

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High-speed (2873 fps) visualization of soap film bursting dynamics has been performed by means of equipment available to a high school laboratory. This paper presents the geometry of the experiment and description of the analysis method of the video frames. We carried out the experiments on the bursting of vertical plane soap films using a circular frame with single central and non-central puncture of the film by a needle. The studies were also performed with simultaneous puncture of the film by two needles. Similar research of the films bursting was done using a non-circular frame in the form of a nonconvex hexagon. In all cases, the rupture line has the shape of a circle. For the first time, the displacement of the circular burst center upwards is recorded and explained. Flapping oscillations of the rupture line border at its movement are confirmed. The oscillating character of the rupture line movement is recorded and explained. In addition, we detected formation of the liquid bridge and its destruction at the interaction of two circular bursts with double puncture of the film.
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I. INTRODUCTION

One meets elastic films of liquid and almost liquid substances everywhere in everyday life and industry. These are: lacquer coatings, cosmetics, chocolate and glaze coatings of confections, membranes of living cells, oil films as environmental pollution of water, etc. Also, films are the construction materials of different foams. Stability and lifetime of the films, peculiarities of their destruction dynamics are some of the fundamental issues of the condensed state physics and other technologies.

Soap films are very good models of thin liquid films. Experimental studies of soap films and bubbles are accessible both to well-equipped scientific and school laboratories. That is why scientists have been studying them for several centuries. Historical information about soap film investigations since the 17th century are reviewed in Ref. 1.

There are many serious studies devoted to different aspects of soap film physics. For example, Refs. 2–4 describe generation methods of giant soap bubbles for public presentations. References 5–8 consider topological properties of soap films formed on spatial frames of complicated forms and possible geometrical transformations from one topological form to another. The results of investigations on the influence of electricity and gas discharge plasma on soap films are presented in Refs. 9–11. Optical interference measurements of soap films' thickness are described in Refs. 12 and 13. Surface tension in the film was measured in Refs. 14–16. Description of different laboratory experiments, including the experiments mentioned in this paper, is collected in Refs. 17 and 18.

The surface tension forces control the shape and properties of soap films. The surface tension in liquids is studied on all levels of physics courses: in schools,[19] colleges,[20,21] and universities.[22] As a rule, these courses consider immovable liquid surfaces in static equilibrium. Meanwhile, surface tension forces could be the reason for the dynamic behavior of the liquid films. Good examples of the hydrodynamic fast process controlled by surface tension forces are the bursting and destruction of a soap film. Experimental study of soap film destruction processes and their analysis will give the students new knowledge about the surface tension in liquid films and their dynamics; the students will gain new experience in registration of fast hydrodynamic processes. These are the educational purposes of this work.

In this paper, we will discuss the process of soap film destruction. Stability and dynamics of soap films bursting have been studied for more than hundred years.[23] In the early years of the research, it became clear that high-speed video recording is necessary to study these processes since the films' bursting takes place in several units or tens of milliseconds. The first record of film bursting was done in 1904 by Jules-Étienne Marey and Lucien Bull, who designed the high-speed camera from army machine gun. Nowadays, high-speed digital video cameras are used to study soap films. The cameras have the recording period of 15 ms,[24] 8 ms,[25] 3 ms,[26] and 1 ms.[27] The cameras used in Refs. 24–27 are rather expensive tools. For example, cameras that are able to record 3000 fps cost $30,000 and higher. Such tools are accessible only to well-funded laboratories.

Recently, a comparatively inexpensive high-speed digital video camera, the Chronos 1.4[28,29] appeared on the market, a camera that is affordable for high school laboratories. The technical characteristics of this camera allow detailed consideration of the peculiarities of the soap films bursting process with sub-millisecond recording period. In this paper, we describe the experiments on soap film bursting using the Chronos 1.4 camera. These experiments allowed, for the first time, the discovery of the novel peculiarities of the burst dynamics: The shift of the circular burst center upwards and the formation of the liquid bridge at a double burst.

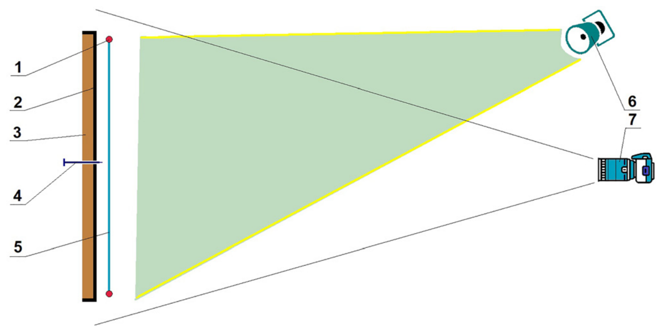


Fig. 1. Scheme of soap film bursting visualization: 1—frame; 2—velvet cover of the screen; 3—screen; 4—needle; 5—soap film; 6—lamp, 7—video camera.

II. GEOMETRY OF EXPERIMENTS

The proposed experimental scheme is simple and could be easily assembled by a teacher and students (Fig. 1). The main element of this scheme is a plastic frame for soap film forming. Mostly, we used a circular frame of 157 mm diameter. In some experiments, we studied the dependence of the frame shape on the form of the rupture line. In these cases, we used a frame in the form of a nonconvex hexagon.

To form soap film, we used solution from a kit for soap bubbles "HC119453 Bubble Blowing Toys" by "HUICHENG" (made in Guangdong, China).[30] This solution is available for purchase at children's toy stores or could be prepared using the recipes from Refs. 3 and 31–34.

The frame was installed vertically against the background of a screen. The screen could be made of any sheet material—cardboard, for example. Its size should exceed the size of the frame. To avoid specks of light, it is necessary to cover the screen with black velvet. Steel needles are located in several holes in the screen. These needles can puncture a soap film at several points. To avoid shielding of the film during video recording, the needles could be pushed by hand from the back side of the screen. Such shielding took place in Refs. 24, 25, and 27.

It should be noted that the needle should be dry before puncturing. If the needle is covered with soap solution, it punctures soap film without bursting it.

The video camera Chronos 1.4 with the objective Computar 12.5–75 mm f/1.2 Zoom was used for the visualization process. The distance from the screen to the camera was 1.5 m. Possible operation regimes of Chronos 1.4 camera are presented in Table I.[28] We found experimentally that the regime at recording period ∼350 μs (2873 fps—the 5th line in Table I) and resolution of 800 × 600 Pix were the optimum ones for our geometry. At smaller recording rate, we observed blurring of the film border; at higher recording rate, the spatial resolution of the frames is not sufficient.

High-speed video recording has one important peculiarity. The quantity of photons hitting the CMOS-matrix during a single frame recording (>350 μs) is small. To get the qualitative image, it is necessary to provide an additional accent light. We found out that additional illumination by means of luminescent and LED lamps is not suitable. Brightness of such light sources oscillates on the main frequency (50 Hz in Russia). We recommend using ambient natural sun light, high power incandescent, or halogen lamps, which do not have brightness oscillations. In our experiments, we used 100 W halogen lamp.

Appendix A presents all materials and equipment used, and their cost.

III. EXAMPLE OF BURSTING PROCESS RECORDING AND METHOD OF DIMENSIONAL ANALYSIS

During recording of soap film bursting (formed on the circular frame), we found that the process takes less than 20 ms in the case of central puncture of the film. Each video record was split into separate frames; each frame was analyzed. Finally, the bursting process is characterized by ∼50 frames. Some frames from one of the video records are presented in Fig. 2.

In the initial analysis, we found that the rupture line shape is circular on all analyzed frames. Locations of the topmost point of the rupture line (point A in Fig. 3), rightmost point of the rupture line (point B), and lowest point of the rupture line (point C) were measured on each frame. The measurement results are expressed in pixels and then recalculated into centimeters. Based on these data, we plotted the laws of motion diagrams $d_{A,B,C}(t)$ for the points (A, B, and C). These diagrams are presented in Fig. 4.

IV. REGULARITIES DISCOVERED

A. Upward shift of the circular burst center

Analysis of the diagrams in Fig. 4 gave us unexpected results. First, the movement diagrams of the points A, B, and C are similar only at the initial stage of the burst opening during ∼5 ms. Later, the curves run away from each other. In

Table I. Parameters of Chronos 1.4 camera (Ref. 28).

Resolution	Max rate, fps	Record time 8 GB, s	Record time 16 GB, s	Record time 32 GB, s
1280 × 1024	1057	4.1283	8.2603	16.5244
1280 × 720	1502	4.1308	8.2654	16.5346
1024 × 768	1771	4.1074	8.2187	16.4411
1024 × 576	2359	4.1108	8.2254	16.4546
800 × 600	2873	4.1436	8.2909	16.5856
800 × 480	3587	4.1419	8.2875	16.5789
640 × 480	4436	4.1977	8.3993	16.8025
640 × 240	8816	4.2049	8.4137	16.8313
336 × 252	15 200	4.3760	8.7560	17.5161
336 × 190	20 020	4.4535	8.9111	17.8262
336 × 96	38 565	4.5275	9.0591	18.1224

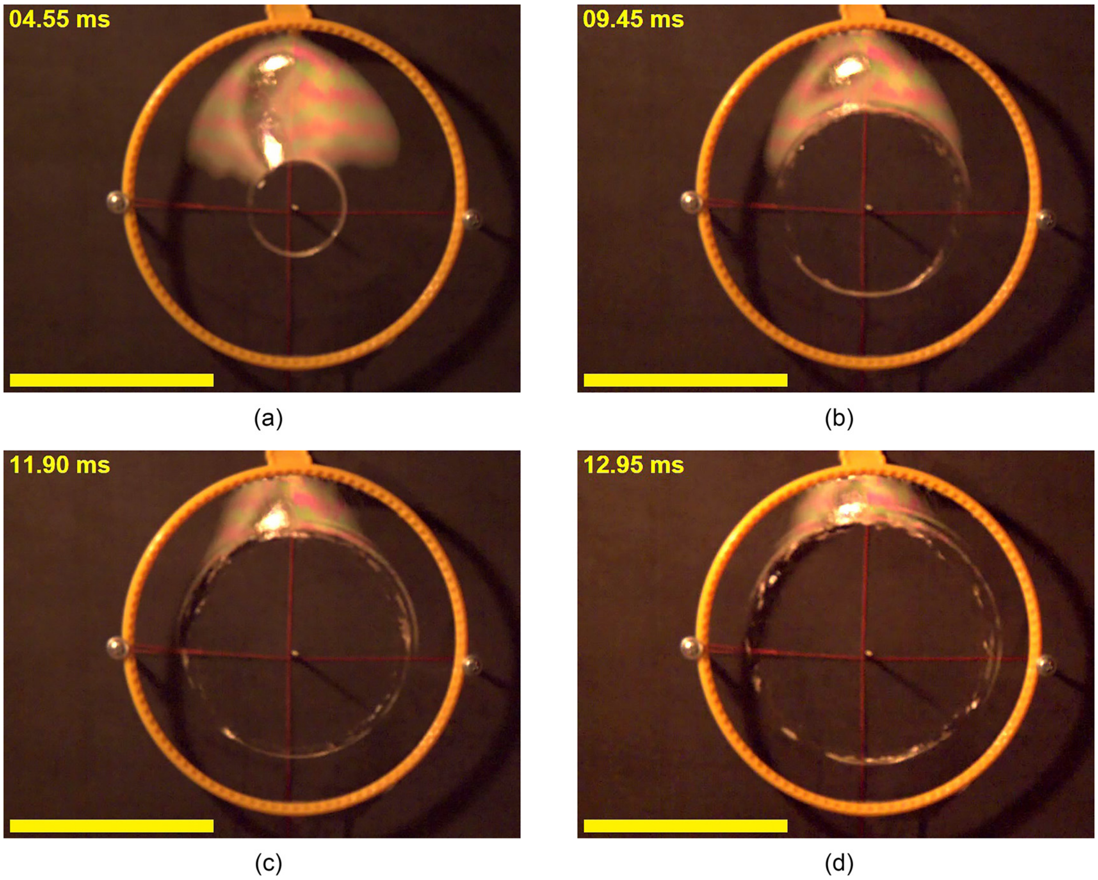


Fig. 2. Some frames from the video record of one of soap film bursting processes with central puncture by the needle. (Time is calculated from the moment of the film puncture, scale bars are 10 cm.)

this case, the point A moves faster than the other ones. The point C is the slowest one. Geometrically, this means that the center of the circular burst shifts upwards. One can easily find the law of motion of the burst center $\delta(t)$ using the formula

$$\delta(t) = \frac{[d_A(t) - d_C(t)]}{2}. \tag{1}$$

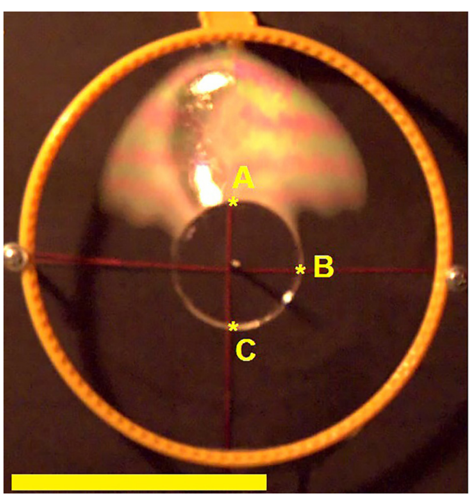


Fig. 3. Momentum position of the points A, B, and C for measurements (scale bar is 10 cm).

A plot of the result is presented in Fig. 5. It appeared that the center of the circular burst shifts upward during the bursting process for ~1 cm. Shift of this center was unexpected; we had found no mention of this effect in the literature. Nevertheless, it can be explained easily.

It is known that if we locate soap film vertically, the Earth gravity force causes draining of the liquid downwards. Within several minutes, the vertical film (initially having similar thickness at all sections) becomes non-uniform in thickness. Thicker sections appear in the lower part. This could be demonstrated by means of optical interferometry.[30] In our experiments, we spent $1-2$ min to install the frame

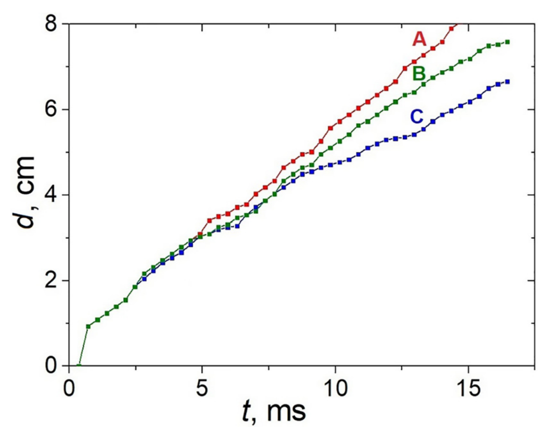


Fig. 4. Motion diagrams of the points A, B, and C. (Distance is calculated from point of the film puncture.)

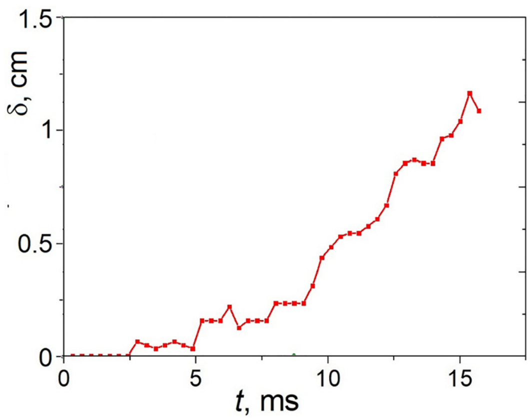


Fig. 5. Diagram of the law of motion of the circular burst center.

with soap film, adjust the recording equipment, and record the process. This time was sufficient for changing the film thickness in different sections.

It was shown experimentally in Ref. 25 that the velocity of the burst opening decreases as the film thickness increases. Reference 35 presents a model of the burst movement. This model is based on the theory of elasticity. It comes from this theory that the velocity v of the point on the rupture line is expressed by the Taylor–Culick formula

$$v = \sqrt{\frac{2\sigma}{\rho h}}, \tag{2}$$

where σ is the surface tension coefficient, ρ is density of the liquid in the film, and h is the film thickness. References 25 and 36–39 present simple derivations of this formula. These derivations are based on analysis of a differential equation of the rupture line border movement taking into account the variable mass. This derivation should be clear for university students, though beyond the typical high school student. Appendix B presents the simplest (from mathematical point of view) derivation of the formula (2) taken from Ref. 39. This derivation is appropriate for high-school students.

Since the point B moves horizontally (the film thickness is constant), the velocity of the point B is constant. So, the law of motion $d_B(t)$ is linear. Since the points A, B, and C are close to each other in the initial state of the bursting process, their motion velocities are almost equal. At the advanced stage of the process, the burst moves on the sections with different thickness of the film; so, the motion velocities of the points are different. This is what leads to the shift of the circular burst center upwards. On the diagram in Fig. 4, this corresponds to the curves running away of the laws of motion $d_A(t)$ and $d_C(t)$ from the linear law $d_B(t)$.

B. Are the bursts always circular?

Let us again turn to Eq. (2). It is clear that the distance from the film rupture line to the frame is not included into the formula. This means that the burst must remain circular with asymmetrical (non-central) puncture of soap film at the circular frame or at the frame in the form of a polygon. Is this true?

Reference 27 presents the image of soap film burst in the center of a square frame. The burst has the circular form. We made several records of soap film bursts in the circular frame and in the frame in the form of nonconvex hexagon. Some frames from these video records are presented in Figs. 6 and 7. One can see that the rupture line shape in these cases remains circular not only at the initial stage of the process—when the rupture line is far from the frame. It is circular even at the late stages, when the rupture line reaches the frame. This does not contradict the theory developed in Ref. 35.

C. What happens with a double puncture of soap film?

Interaction of two bursts is very interesting. These bursts are formed with simultaneous puncture of soap film by two needles. There seems to be no previous research on this. It turned out that a researcher can punch the needles with his or her palm and make two punctures in the film with a difference of <2 ms.

Some frames from the video record of the bursting process with almost simultaneous puncture of the film are presented in Fig. 8. According to the video records, the interaction process starts when the rupture lines of two bursts reach each other. A liquid bridge is formed between the bursts during the interaction; it becomes thinner in time and then breaks. Drops of the liquid, remaining at the location of the bridge, disappear rather fast (do they evaporate or become out of focus of the camera?). The visually observed period of the bridge breaking is $\sim$1 ms.

D. Observation of ripples near the rupture line

Many video records show a striped structure with a period of several millimeters (Fig. 9). Such structure was observed earlier (see Fig. 7.13 from Ref. 38 and Fig. 3 from Ref. 40). The nature of the stipes is ripples of capillary waves.[39,41]

V. CRITERIA OF EXPERIMENTS APPLICABILITY TO EDUCATIONAL PROCESS

The possibility of using new demonstration and research experiments in teaching is based on the following criteria:

(i) acquisition of new knowledge and experience by the students;
(ii) simplicity of the experiments for understanding at the given level of instruction;
(iii) accessibility of materials and equipment, including their cost; and
(iv) safety of the experiments.

Let us consider how these criteria are realized in our work on soap films bursting.

(i) As has been already mentioned, the students can acquire new knowledge on surface tension physics. This physics subdiscipline is studied on all educational levels of physics: from school to university. In the physics textbooks, surface tension is usually considered to be a static and permanent process. After a demonstration of soap film bursting, the students will learn that the surface tension forces can also cause dynamic flows of liquids. The students will also know that the rupture border velocity is constant and conforms to the Taylor–Culick formula. During the experimental work, the students will gain experience in high-speed recording of the process, they will learn how to build the geometry of the experiment, choose

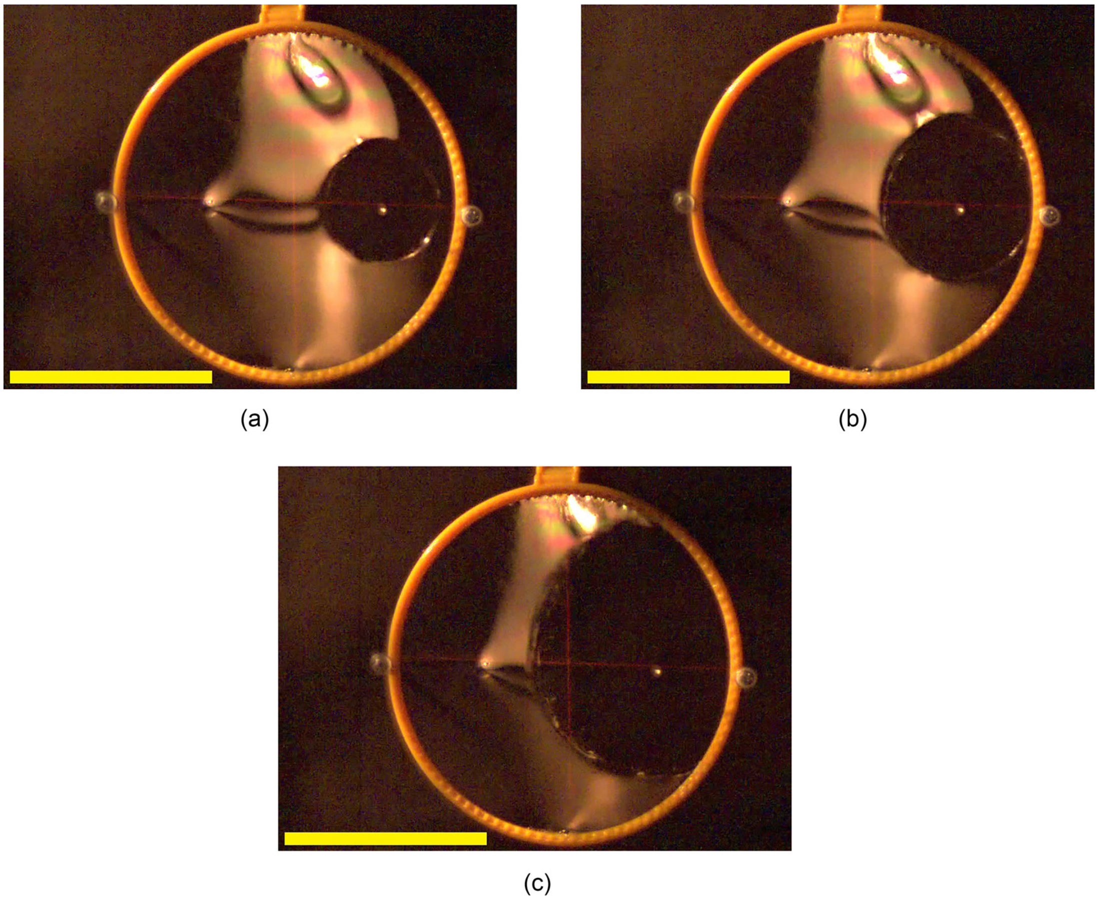


Fig. 6. Some frames from the video record with non-central film puncture using the circular frame. (Scale bars are 10 cm.)

the perspective, shooting rate, and luminescence, how to work with video and analyze it.

(ii) Assembly, adjustment, and performance of the experiments are simple and do not require special training. Let us note that at least two persons are required to perform the experiment: The first person ruptures the soap film, and the second one records the video from a distance of ∼1 m from the film.

(iii) The Chronos 1.4 camera is the most expensive piece of equipment in the experiment, though this camera is quite affordable compared to other cameras with similar characteristics. Other materials and equipment are quite affordable; total cost of the equipment is not more than ∼$3,000 (please, see Appendix A).

(iv) As a rule, fast hydrodynamic processes are high-energy processes (for example, shocks, explosions, or electric breakdowns). However, the experiments with soap film bursting do not require high power expenditures; do not use hazardous and dangerous substances, high voltage, heavy items, etc. That is why these experiments are completely safe.

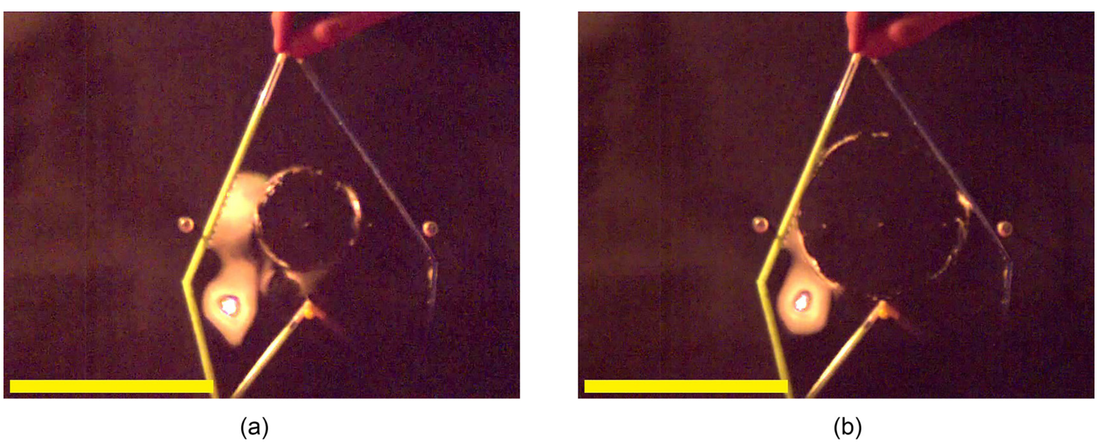
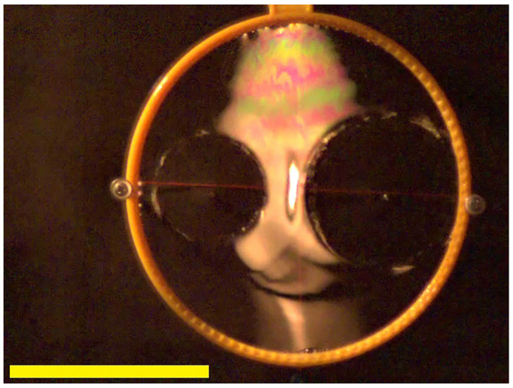
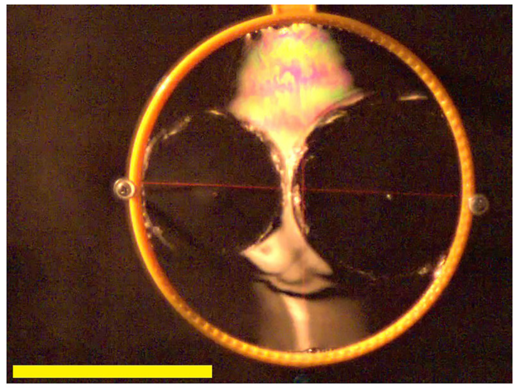


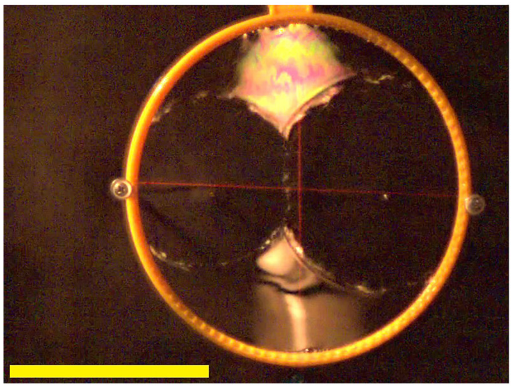
Fig. 7. Some frames from the video record with the film puncture using nonconvex hexagonal frame. (Scale bars are 10 cm.)



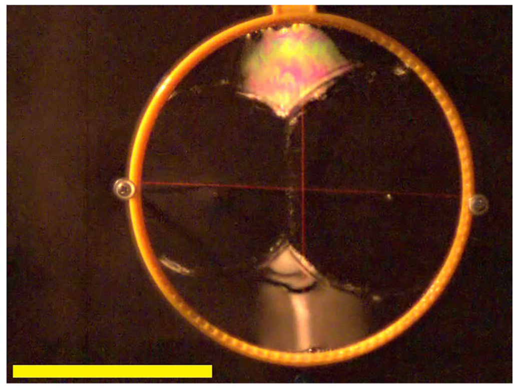
(a)



(b)



(c)



(d)

Fig. 8. Some frames from the video record with double puncture of the film using the circular frame. (Scale bars are 10 cm.)

VI. CONCLUSION

In this work, we performed high speed (2873 fps) visualization of soap film bursting dynamics using the digital video camera model Chronos 1.4, accessible to a school physics laboratory. Geometry of the experiment and description of the video record analysis are presented. We carried out experiments on the bursting of vertical plane soap films using a circular frame with single central and non-central puncture by a needle. Also, studies were performed with simultaneous puncture of the film by two needles. Similar research on films bursting was done using a non-circular frame in the form of nonconvex hexagon. In all cases, the rupture line was found to have the shape of a circle.

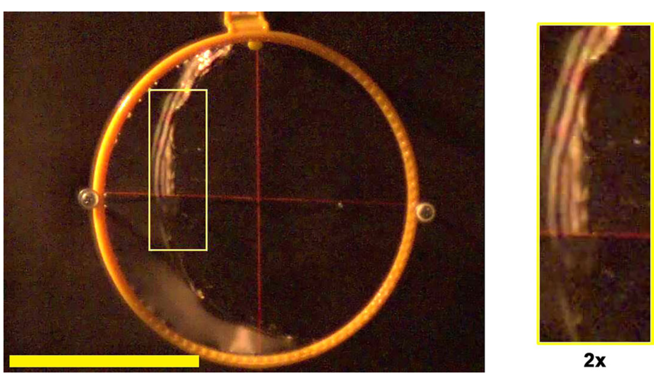


Fig. 9. Images of the ripples. Top view (right image—enlarged view of a fragment, scale bar is 10 cm).

For the first time, the upwards displacement of the circular burst center is recorded and explained. Ripples of the film near the rupture line are observed. We also detected formation and destruction of the liquid bridge at the intersection of two circular bursts from a double puncture of the film.

The educational purpose of the experiments is to teach the surface tension phenomena in liquids films and high-speed visualization of hydrodynamic phenomena, which could not be discerned with unaided eye. Such experiments may be proposed for school, college, and university laboratories.

ACKNOWLEDGMENTS

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APPENDIX A: EQUIPMENT AND MATERIALS

Camera: Chronos 1.4, $2.499 (https://www.kickstarter.com/projects/1714585446/chronos-14-high-speed-camera?token=2dde9ee4)

Objective: Computar 12.5-75 mm f/1.2 Zoom, $309 (https://www.bhphotovideo.com/c/product/889132-REG/computar_M6Z1212_3S_2_3_12_5_to.html)

Memory card: SanDisk Ultra 32GB microSDHC UHS-I card with Adapter - 98MB/s U1 A1 - SDSQUAR-032G-GN6MA, $9 (https://www.amazon.com/SanDisk-Ultra-microSDXC-Memory-Adapter/dp/B073JWXGNT)

Circular frame + bottle with soap solution: 2 wands soap bubble stick bubble blowing toys for outdoor game, $2 (https://www.alibaba.com/product-detail/2-wands-soap-bubble-stick-bubble_60446512864.html?spm=a2700.galleryofferlist.0.0.12c750b4lX3oTt)

Bosch BT150 Compact Extendable Tripod with Adjustable Legs BT 150, $34.26 (https://www.amazon.com/Bosch-BT150-Compact-Extendable-Adjustable/dp/B00SIL5O36/ref=sr_1_2?adgrpid=79685717977&gclid= Cj0KCQiAmZDxBRDIARIsABnkbYQNeM544-twVKEv_ucCagVqrSz8NdE2sGFMt1ekA06w67MFmdyy1IkaAoNqEALw_wcB&hvadid=393498678610&hvdev=c&hvlocphy=9040935&hvnetw=g&hvpos=1o2&hvqmt=b&hvrand=12185237020977917042&hvtargid=kwd-3623188687&hydadcr=2745_11210436&keywords=bosch+tripod&qid=1579425851&sr=8-2)

220V LED FloodLight 10 W 30 W 50 W 100 W Reflector LED Flood Light Waterproof IP65 Spotlight Wall Outdoor Lighting Warm Cold White, $21 (https://www.aliexpress.com/item/32955363802.html?spm=a2g0v.search0302.3.22.54fc7a82Vh1h3j&ws_ab_test=searchweb0_0,searchweb201602_0,searchweb201603_0,ppcSwitch_0&algo_pvid=23c0782b-e841-4d57-a373-85a3b61ba2bc&algo_expid=23c0782b-e841-4d57-a373-85a3b61ba2bc-3)

J78 R7S linear halogen lamps 60 W 80 W 100 W, $0.358 (https://www.alibaba.com/product-detail/J78-R7S-linear-halogen-lamps-60W_60651216602.html?spm=a2700.galleryofferlist.0.0.5d081d5d1df1JN)

The total cost is $2875. Prices are relevant for January 2020.

APPENDIX B: DERIVATION OF THE TAYLOR–CULICK FORMULA (2)

We present here a simple derivation of the Taylor–Culick formula of Eq. (2) taken from Ref. 39. Two statements that were found in the experiments are used in this derivation:

- The film thickening is formed on the rupture border; usually, it is called the rim;
- Mass of the rim increases during movement, and its velocity is constant.

The equation of the rim movement considering the variable mass m per unit of its length is written here (we use the differentiation rule for product)

$$\frac{d}{dt}(mv) = v\frac{dm}{dt} + m\frac{dv}{dt} = 2\sigma. \tag{B1}$$

The factor of two on the right side of Eq. (B1) appears here because the film has two surfaces—front and back ones (Fig. 10).

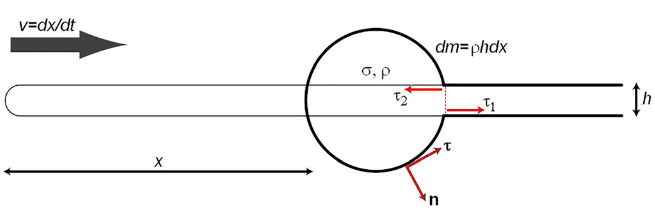

Fig. 10. This scheme explains derivation of the Taylor–Culick velocity (from Ref. 39 with reindexing). Here, **n** and τ are the unit vectors: Normal and tangent to the rim surface, respectively; $\tau_{1,2}$ are the surface tensions of the different sides of soap film.

From the experiments, we know that the rim velocity is almost constant. It is easy to understand the constancy of the velocity. Indeed, the rim mass and the released energy of the surface tension transforming into the kinetic energy of the rim similarly depend on coordinate x during movement, since they are both proportional to x. This is possible when $v = const$.

Since the velocity v is constant, it remains

$$v\frac{dm}{dt} = 2\sigma. \tag{B2}$$

The rim mass rate is written as

$$\frac{dm}{dt} = \rho h v. \tag{B3}$$

Combining Eqs. (B2) and (B3), we get the Taylor–Culick formula (2).

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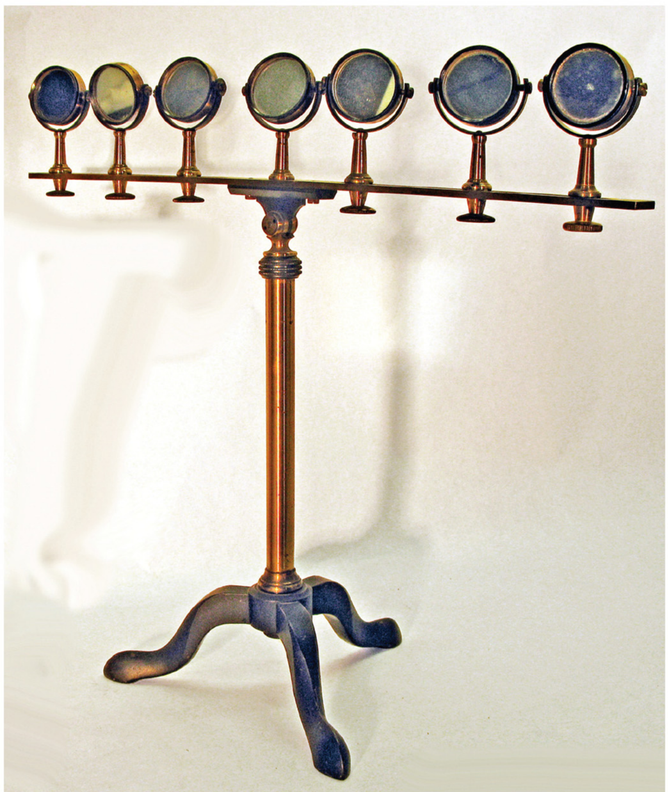

Seven Mirror Device

A beam of white light striking a triangular prisms comes out the other side in a spectrum. Isaac Newton decided that there were seven “colors” in the spectrum (he added indigo to the six usual colors because seven was a sacred number). The seven mirrors of this device catch the portions of the spectrum and redirect them to the same spot on a wall. The result is a white spot. The seven mirror device was quite common in the 19th century, and has been out of use since then. This example, made by Duboscq of Paris in the latter part of the 19th century, is in the apparatus collection at Union College in Schenectady, New York. (Picture and text by Thomas B. Greenslade, Jr., Kenyon College)