Problem No 4 (2010). “SOAP FILM”

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Problem: ***Create a soap film in a circular wire loop. The soap film deforms when a charged body is placed next to it. Investigate how the shape of the soap film depends on the position and nature of the charge***.

1. The Soap Film Structure

Let’s start investigation of this problem by considering the soap film structure[1] briefly. Soap film is formed by surface active agents (Surfactants). There are two layers of soap molecules, between which there is water (see Figure 1[1,2]).

A soap molecule is divided into positive Na^+ and negative $C_{17}H_{35}COO^-$ ions.

Negative ions collect on the surface of film and they **form surface structure**.

Between two layers of film there are water and Na^+ ions.

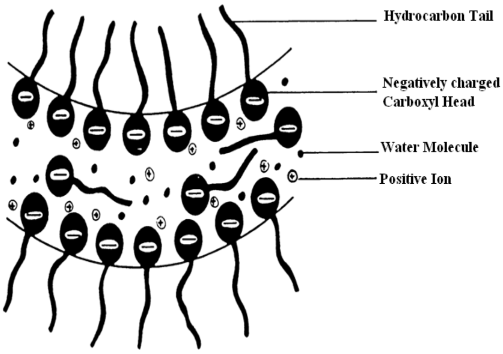

Figure 1. Soap film structure.

Soap molecules play the important role in the film formation[1,2]:

- ✓ Negative ions $C_{17}H_{35}COO^-$ form the surface structure of soap film;
- ✓ Soap molecules decrease the evaporation of water;
- ✓ They also decrease the surface tension.

Here we want to note that this difference in the positive and the negative ion distribution in a soap film leads to a very interesting phenomenon, which will be discussed below.

In some of our experiments we added a small amount of glycerin to soap, because the glycerin decreases the water evaporation from the surface and also stabilizes the soap film[1,2]. So, due to the glycerin a soap film gets an "extra duration of life" and becomes more elastic.

2. The experimental Setup

Now let us describe our experimental setup (for better quality color photos please see our presentation [3]). We used:

- A voltage source - an old CRT monitor, which provides $27\,000\ V$;
- Electrodes of different forms;
- Different distances between the electrodes and the soap film;
- A metal loop (frame) for the soap film - grounded one and also not grounded;
- A dielectric loop (frame);
- Different sign of body charge (and this gave different results!!!).

Figure 2. Experimental setup.

3. A spherical charged body

We began experiments with an interaction between a spherical charged body and a soap film. In our experiments we used the frame for soap film of radius $a \sim 5\ cm$. Too small frames were not convenient for making observations and measurements, while too large – to get stable films and to avoid influence of even small air flows.

It was observed, that:

– As larger the distance d between sphere and film - the less the influence (deformation);

– In the case of $d \sim 5\ cm$, the height h of the film deformation in the center was about $1\ cm$ and the film remained stable;

– For the small $d \sim h$, the stable state did not occur. Film continued to stretch, discharge developed and film exploded.

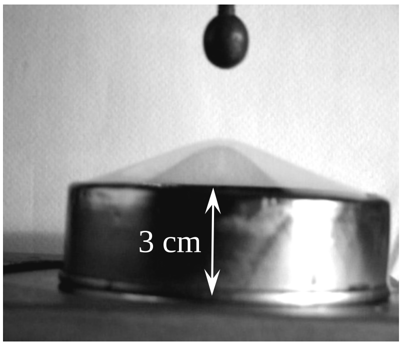

Figure 3.

Let us explain this theoretically. When the charged body approaches the film, the charges on the latter will be redistributed (since the film is a conductor) in the way to make the film equal-potential. Electric field on the film will be compensated by these redistributed (Induced) charges. On the film, near the external charge, the opposite-signed charges will gather (they are attracted by this external charge and thus the film will stretch towards it – see Figure 3), while far from it – the same-signed charges are gathered. Generally, the distribution of charges on the film will be quite complicated, but approximately the problem of “soap film - external charge interaction” can be solved by using the “Electrostatic Image Method”. We will assume the external charge as a point charge and the film shape as a spherical segment.

In such interaction the electrostatic force is balanced by the surface tension force. The latter can be calculated by means of Laplace equation while the electrostatic force between the charge and the film we calculated using an "electrostatic image method". Equating the Coulomb and the surface tension forces we can calculate the dependence of h on the external sphere charge Q and on d. We will use the approximation, when the deformation is much less than the loop radius and the distance to the charged sphere.

Electric force.

Thus our assumptions are the following:

- The external field redistributes the charges on the film;
- The film surface is equal-potential;
- The interaction between the charge and the grounded sphere film can be "effectively" presented as the interaction between the two point charges;
- The value and the place of "effective" charge must give equal-potential film surface;

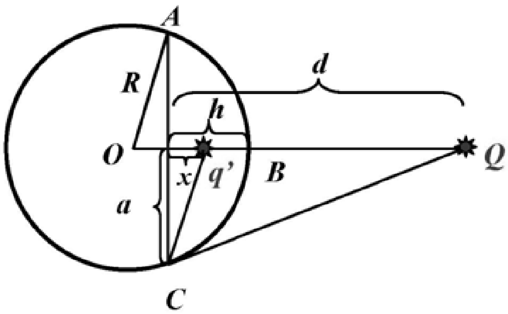

Figure 4.
The method of electrostatic image.

- We assume that the film is a sphere segment ABC of the height h;
- AC – the loop (frame) of a radius a;
- Q – the external charge, at the distance $d >> h$;
- q' – the "effective" charge at the distance x from the loop.

From the Figure 4 the condition of $\varphi_B = \varphi_C = 0$ (a grounded film) leads to the following values:

$$x = \frac{2a^2h - a^2d + h^2d}{a^2 + 2dh - h^2} \quad ; \quad q' = -Q\,\frac{a^2 + h^2}{a^2 + 2dh - h^2} \quad , \qquad (1)$$

and the effective electrostatic interaction force will be:

$$F_k = kQ^2\,\frac{(a^2 + h^2)(a^2 + 2dh - h^2)}{4(d-h)^2\,(a^2 + dh)^2} \quad . \qquad (2)$$

This force must be balanced by the surface tension force.

Surface tension force.

Using the Laplace formula $P_l = 4\sigma_0 / R$ and taking into account, that

$$R = \frac{a^2 + h^2}{2h}$$

we obtain

$$p = \frac{4\sigma_0}{R} = 4\sigma_0\,(\frac{2h}{a^2+h^2}) \ .$$

If we write down $F_l = pS$, we will get that the force of the surface tension is

$$F_l = 8\pi\sigma_0\,h \ . \qquad (3)$$

Balance of Electrostatic and Surface tension forces.

Using the force equilibrium condition $F_k = F_l$ for (2) and (3) we get:

$$kQ^2 = \frac{32\pi\sigma_0\,h\,(d-h)^2(a^2 + dh)^2}{(a^2+h^2)\,(a^2 + 2dh - h^2)} \ . \qquad (4)$$

It is quite a complicated formula, so to make it clearer, let us use the approximation, when $h \ll a;\ h \ll d.$ We can do it in our case, since the film stretch in our experiments was small compared to the frame radius. In this approximation the equations (1),(2),(4) get the form:

$$x \approx 2h - d \ ; \quad q' \approx -Q \quad ; \quad F = kQ^2/(4d)^2 \ ;$$

$$kQ^2 = 32\pi\sigma_0 h d^2 \ , \qquad (5)$$

where from we get the dependence of h on Q and d:

$$h = \frac{k}{32\pi}\cdot\frac{Q^2}{\sigma_0 d^2} = \frac{1}{128\,\pi^2\,\varepsilon_0}\cdot\frac{Q^2}{\sigma_0 d^2} \ . \qquad (6)$$

Let's calculate h for our experiment. This dependence is given on the graph.

For a $1cm$ radius charged sphere, at the potential $\varphi = 27\ 000\ V$, we get:

$$Q = C\varphi = 4\pi\varepsilon_0 r\cdot\varphi \approx 3\cdot 10^{-8}\ Coulomb.$$

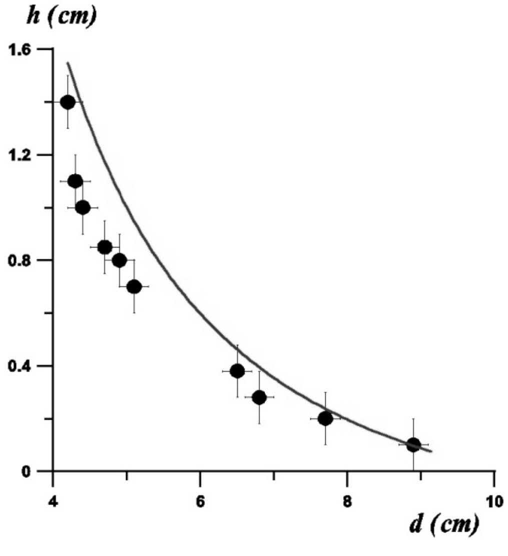

Figure 5.

The dependence $h(d)$ for the stable states: (experiment - points; theory - curve).

Noting that $\sigma_0 \approx 25 \cdot 10^{-3}$ N/m, for the distance $d = 5$ cm from (6) we get $h \approx 1$ cm, that is quite near to our experimental results.

Let us make some notes. From (3) and (2): $F_l \sim h$; $F_k \sim 1/(d-h)^2$. If $h << d$, the F_l increases with h faster than F_k. So the stable equilibrium is reached. If $h \sim d$, situation is opposite - F_k increases with h faster than F_l, so the film stretches and explodes.

4. A flat charged body

By the flat charged body the film deformation was larger (see Figure 6) because the field was stronger.
However without grounding the stretch of the film was significantly less because in that case the ions could not "leave" the film.

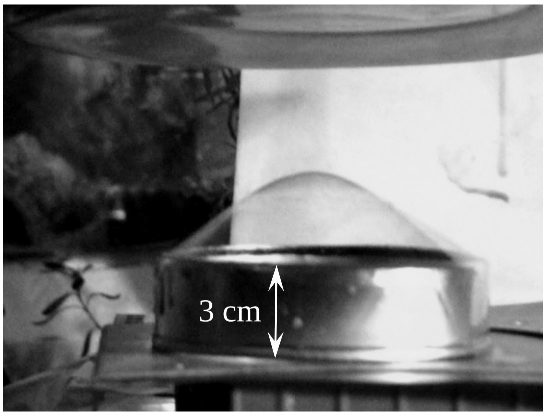

Figure 6.
Flat charged body.

6. An approximately uniform field

To obtain the uniform field we used two parallel large lids. The bottom lid was grounded while to the top lid the high voltage was applied. The film was formed on a plastic (dielectric) loop. In the uniform field the film did not stretch, due to the force symmetry.
In the strong field the film simply was torn by the forces acting on the positive and negative charges.

Figure 7.
Sharp-ended body.

7. Interaction of film with charged nail.

In this case the soap film did not stretch out, but the dip was formed, as if there blew the wind from above (see Figure 7). The observed dip (instead of a "hill") was caused by so called "electric wind", which blew rather strong and this strength was greater than the strength of attraction. Electric wind takes place when the density of charge on the electrode is very high (like the case of nail-type sharp electrode) and electric field near it is very strong. The field at the bottom of the nail polarizes the air molecules and strongly repels the electrons. They hit the film and form the above-mentioned dip. The fact that this wind was caused by charged particles we proved by the following experiment. Instead of soap film we placed the detector of charged particles and it fixed a large amount of accelerated particles.
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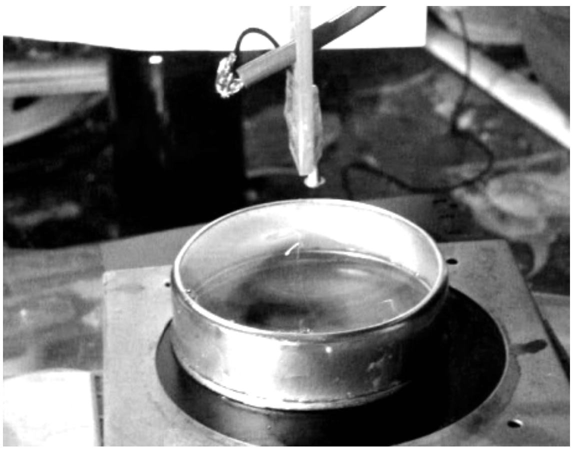

Figure 8.
Small-headed charged body.

8. Interaction of film with small-headed charged body.

In this case the observed behavior reveals both processes - the electric wind and the attraction towards electrode. Both – the "dip" and the "hill" are formed (See Figure 8).

9. *The asymmetry with respect to the change of poles.*

As we mentioned in the beginning of this article, the difference in the positive and the negative ion distribution in soap film causes a very interesting phenomenon. It took place when we changed the poles, i.e. the charge sign of the body. It seems to be the most interesting result and now let's carefully consider it.

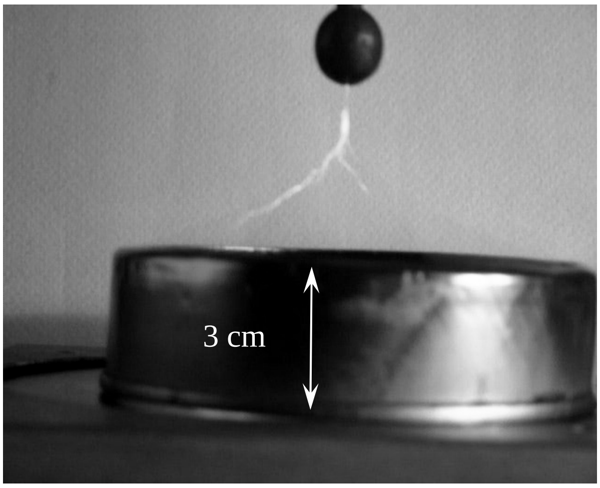

Figure 9.
Discharge (yellow). Positively charged body.

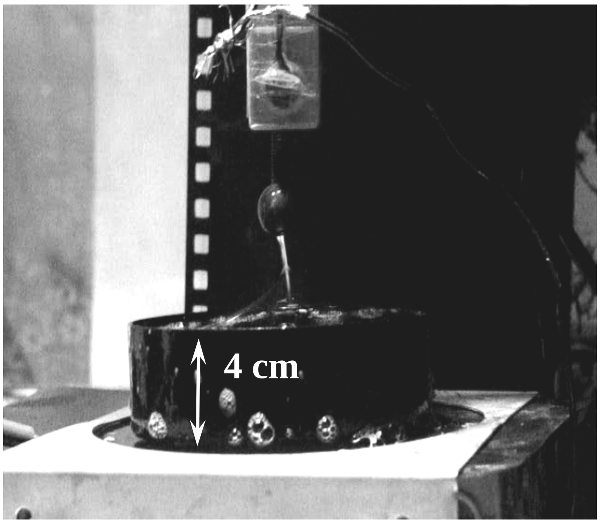

Figure 10.
Discharge (blue). Negatively charged body.

In our experiments we observed, that change of the poles (i.e. charge sign of the body) affects the shape and the color of discharge on the soap film. Parameters of spark are dependent on the sign of the electrode charge. When electrode was charged **positively**, discharge was **spread and yellow, while** when the electrode was charged **negatively,** discharge was **bluish and straight.**

What is the reason of this?
At high temperatures the atoms emit the electromagnetic waves (photons). Frequency of emitted light depends on the transition energy between two levels in atom: $E_{Photon}=h\nu$, where h – is Planck constant, and ν - frequency of emitted light. It is known, that ***Sodium (Na)*** emits yellow light, while ***Nitrogen*** - bluish-lilac light. Thus we can conclude that when electrode is charged negatively the light is emitted by the atoms of ***Nitrogen*** (which are present in air) while in the case of **positively** charged electrode, the light is emitted by ***Sodium (Na)*** atoms. Why it is so?

The Negative external charge accelerates the electrons toward the film. The accelerated electrons strike the ***Nitrogen*** atoms of air and cause their **bluish-lilac** emission. Also, in this case the positive Na^+ ions in soap are attracted by the negative external charge, move along the film freely towards the point nearest to this external body, concentrate there and cause the *straight form of discharge*.

In the case of **positive external charge** heavy ions of air accelerate towards the film. These ions hit the film and punch out of it the positive Na^+ ions which form the "cloud" above the film. So the discharge proceeds in this "cloud" of positive Na^+ ions. This gives the **yellow** color of discharge. Besides, in this case the punched out Na^+ ions are attracted by the negative ions of soap (these negative ions form the soap film structure and are more or less "spread-fixed" around the film surface area). Thus the *discharge becomes more "spread"* (here we see the discharge shape asymmetry with respect to pole sign. It is caused by the soap film ionic structure – different "flaw freedom" degree of the positive and the negative ions). In this case we also saw that most upper part of the spark (which is above the cloud of positive Na^+ ions) is blue, while the main yellow region is within the cloud of the punched out Na^+ ions.

As we observed, the discharge destroys the film.

10. *Conclusion.*

In this work we studied the soap film interactions with the charged bodies. The different shapes of the charged bodies were tested and the resulting film deformations were examined

We found out that film deformation strongly depends on:

- The shape of the charged body
- The charge value
- The distance from the film
- The grounding of the loop on which the film is formed
- The soap film structure

Also, a very interesting phenomenon of the discharge asymmetry with respect to the change of poles was observed. In the case of Negative external charge the straight bluish-lilac discharge takes place, while in the case of Positive external charge – the "spread" yellow discharge. We explained it by the specific ionic structure properties of a soap film.

Finally I want to thank my grandfather Tengiz Barnaveli for his help in the experiments with the high voltage.

References

[1] Cyril Isenberg. The science of Soap Films and Soap Bubbles. Dover Publications, NY 1992.
[2] http://www.soapbubble.dk/en/bubbles/
[3] http://solutions.iypt.org/uploads/2010_GE_Soap_film_Alexander_Barnaveli_1321459517.pptx