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Charging of a single soap bubble

***Abstract**. The process of charging (electrification) of a single soap bubble is presented in this paper. It is shown that the bubble is charged up to its maximum possible charge as calculated from Rayleigh limit. Values of the (Q/m) obtained for the single bubbles were on the level of 1.8–4.8 mC/kg, and thus the bubble trajectory in air is clearly affected by electrostatic forces.*

***Streszczenie.** W niniejszym artykule przedstawiono proces elektryzacji pojedynczej bańki mydlanej. Pokazano, że bańka jest naelektryzowana do maksymalnego możliwego ładunku obliczonego (limit Rayleigha). Uzyskane wartości paramertru (Q/m) dla pojedynczych baniek były na poziomie 1,8–4,8 mC/kg, a zatem lot naelektryzowanych baniek będzie silnie zależny od sił elektrostatycznych. (**Elektryzacja pojedynczej bańki mydlanej**).*

Keywords: soap bubble, aerosol, induction electrification
Słowa kluczowe: bańka mydlana, aerozol, elektryzacja indukcyjna

Introduction

Charging (electrification) of aerosol particles is used in many technological processes, such as painting, applying thin layers, disinfestation. Electro-aerosols are also widely used in medicine and agriculture. To form aerosol pneumatic, hydraulic, ultrasonic dispersion techniques are commonly used. For the charge application induction, conductive and corona charging methods are used [1, 2].

The main method of evaluation of the effectiveness of electrification process is (Q/m) parameter defined as a ratio of charge of the aerosol particle to the mass of this particle.

The higher the value of the (Q/m) parameter is, the more the trajectory of the charged particle depends on electrostatic force and less on the force of gravity. It is assumed that the electrostatic force should be dominant if (Q/m) ratio is greater than 2 mC/kg [2].

Due to the wide range of electro-aerosol applications, there is a need to search for methods to increase the efficiency of their production, i.e. to obtain aerosols characterized by high (Q/m) parameter values with low energy cost. One of such methods may be obtaining electro-aerosols by electrification of a nanometric liquid membrane, for example, a soap bubble. Soap bubble is hollow inside thus has a small mass, compared to a droplet with similar radius. Because charge is mainly accumulated on surface, it leads to the possibility of production droplets characterized by a high (Q/m) ratio, from bursting bubbles.

Such idea was proposed in [3] as a method of obtaining small droplets for an electrohydrodynamic generator.

Soap bubbles and electric charge

A soap bubble is defined as a closed thin layer (membrane) of liquid (usually a mixture of water and detergent) filled with gas.

Parameters characterizing a bubble such as a film thickness, diameter, mass, durability depend on the used soap solution, the method of production and environment. The thickness of the liquid layer ranges from tens to over a thousand nanometers. Due to the phenomenon of gravitational drainage and evaporation, the film thickness changes over time. For these reasons, the bubbles are much thinner on the top than on the bottom [4, 5, 6].

In paper [7] the soap bubbles mass m_b, i.e. the mass of the soap film, for radii in the range of 25–55 mm has been given. For bubbles with a radius of 25 mm its mass is 5 mg, and for bubbles with a radius of 55 mm is 27 mg.

The film rupture thickness (i.e. the thickness of the soap film when a bubble starts to burst) depends on bubble size and surface tensions. Bigger bubbles and those characterized by higher surface tension have higher rupture thickness. In [8] rupture thicknesses in the range of 0.13 to 0.98 μm were reported (for bubbles with radius in the range of 5 to 15 mm, and surface tensions in range from 34 to 50 mN/m).

When a soap bubble bursts it produces droplets of various sizes [8, 9]. In [9] maximum measured droplet diameter was 500 μm. In [8] the droplets of diameter from 0.5 to 10 μm were observed. The droplets distribution after bubble bursting is affected by bubble size, its lifetime, surface tension and used soap solution [6].

Maximum charge that can be applied to a droplet of the specific radius r can be calculated using relation called the Rayleigh limit [10]:

$$Q_{\max} = 8\pi\sqrt{\varepsilon_0 \cdot \gamma \cdot r^3} \tag{1}$$

where: γ – surface tension [N/m], r – droplet radius (in this case – radius of bubble r_b) [m], ε_0 – free space permittivity [F/m].

Assuming the radius of the bubble is 25 mm and the surface tension γ is 35 mN/m [8], the maximum charge of the bubble should be on the level of 55 nC. Dividing this by mass 4.5 mg [7] gives expected (Q/m) value around 12 mC/kg. This is a value much higher than required 2 mC/kg.

Soap bubbles productions

A mixture of water, detergent and glycerine was used to produce soap bubbles. The mixture was characterized by electric conductivity on the level of 14.9 μS/cm. The bubbles were blown out using a metal tube/pipe with a diameter of 5 mm. Produced bubbles are shown in Figure 1 – two extreme cases. Soap film drainage is showed in Figure 2. The photographs were taken by digital camera Fuji FinePix S5700.

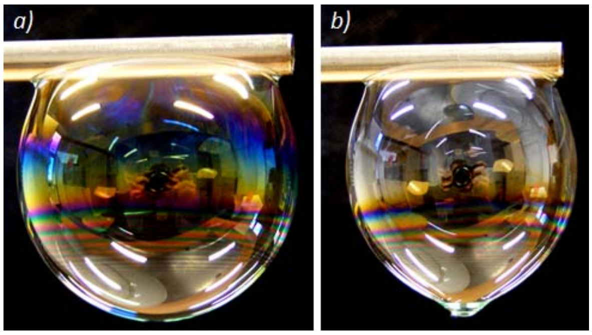

Fig.1. Produced bubbles - two extreme different shapes: a) round bubble, b) ellipsoid bubble

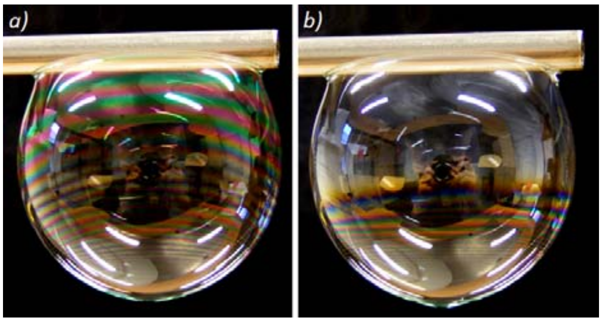

Fig.2. Observation of water film drainage on a single soap bubble: a) bubble about 20 s after blowing (time needed to prepare camera settings), b) bubble after additional 5 s, just before bursting

The obtained bubbles had radius r_b in the range of 15–25 mm. The lifetime of the bubble was 20–35 s. In Figure 1.b a relatively large water droplet under bubble is visible. In Figure 2, the forming of such water droplet in the bottom part of the bubble can be seen.

Based on colour matching of interference pattern (fringes) it can be estimated that film thickness of bubble top is 500–900 nm in Figure 2.a, and just before bursting (Figure 2.b) is less than 200 nm [4, 6]. These are the values typical for soap bubbles [4–6, 8].

The bubble mass measurements were carried out using a laboratory scale OHAUS PA 413/1, the obtained values were within the range of 9–24 mg. These values are several times higher than expected ~4.5 mg value as presented in [7]. Because the bubble thickness is normal, this difference in mass is most likely caused by the water gathering in the bottom part of the bubble and forming a droplet there, as shown in Figure 1b. It should be noted that because of water evaporation effect, these results should be treated as a rough estimation of bubble mass m_b.

Due to this fact, in case of produced bubbles, expected (Q/m) values are on the level of 2–6 mC/kg.

Observation of bubble behaviour in the electric field

First, the observations of bubbles in an electric field were carried out in the setup shown in Figure 3. High voltage was applied directly to a metal pipe MP and in extension to the soap bubble SB. The mechanical switch S, connecting DC high voltage supply (HV DC) and metal pipe MP, was used to ensure that the full voltage is applied to the bubble. Under the bubble, a grounded electrode E was placed. The distance between electrode E and metal pipe MP was h = 155 mm. In all experiments described below only positive polarity voltage was used.

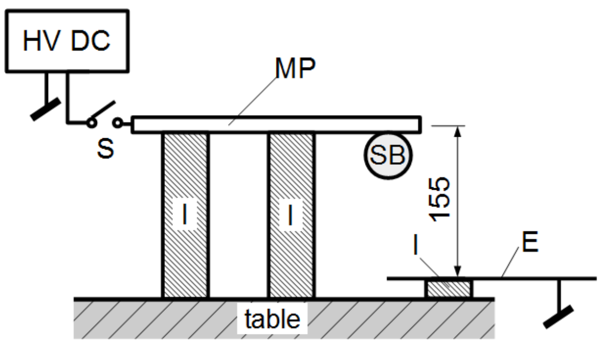

Fig.3. Scheme of setup for soap bubble observation. SB – soap bubble, S – mechanical switch, MP – metal pipe, HV DC – DC high voltage supply, I – insulating supports, E – grounded electrode

In order to analyze setup shown in Figure 3 a 2D model was made using COMSOL Multiphysics software. The geometry of the model was based on the setup geometry showed in Figure 3. In simulation it was assumed that: the soap bubble SB is conductive (i.e. is equipotential with potential equal to that applied to metal pipe MP); the electrode E was on ground potential; the relative permittivity of the surrounding medium was equal to ε_r = 1 (as for air); the relative permittivity of the insulating supports was equal to ε_r = 2; on the model external boundaries there was no normal electric field component (only tangential).

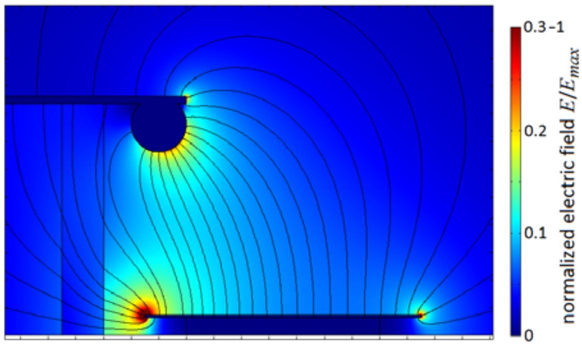

Fig.4. Normalized (to maximum value) electric field distribution and electric field lines just after HV application (soap bubble is undeformed)

Soap bubble shape without and with the electric field is showed in Figure 5. The bubble deforms in the direction of electric field lines shown in Fig.4.

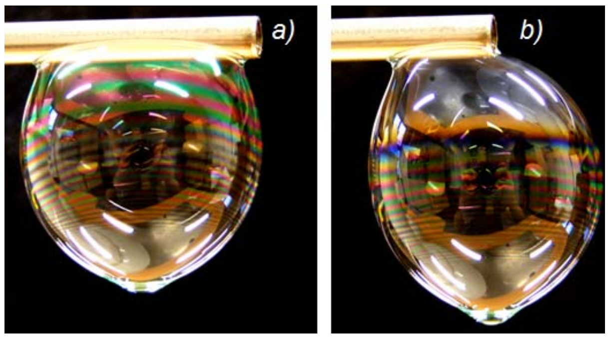

Fig.5. Same soap bubble a) without an electric field, b) after applying 6 kV voltage on the metal pipe

Bubbles did not burst immediately after voltage applying but after some delay. At this stage of research, no noticeable difference was observed for the lifetime of neutral and charged (U_e = 6kV) soap bubbles. Most likely, at this level of electrification, factors other than the bubble's charge determine the bubble's lifetime. This means that the bursting was caused by reaching the rupture thickness and not by charge directly.

If the charging voltage U_e is greater than 6 kV, the bubble slips off the metal pipe and lands on a grounded electrode. A trajectory of bubble sliding from the pipe is shown in Figure 6. This trajectory has a shape of electric field lines showed in Figure 4.

The ejections distance z in the function of the charging voltage U_e is shown in Figure 7. It can be seen that after applying a voltage greater than U_e = 10kV the ejections distance z is constant and equal to z = 85 mm.

The fact that the bubble slips from metal pipe gives the possibility to measure bubble total charge Q with a Faraday cage.

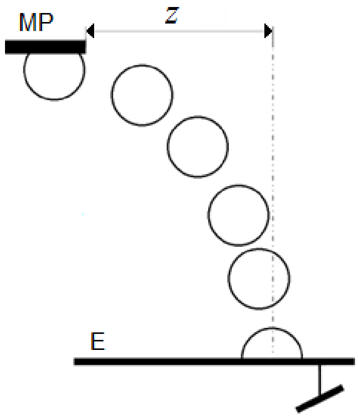

Fig.6. Soap bubble falling off from metal pipe – image based on images from the recorded film using a digital camera. z – ejection distance

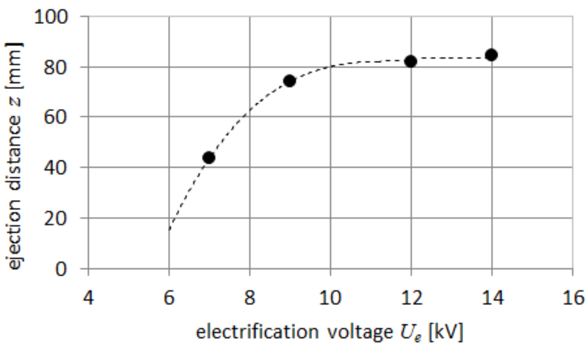

Fig.7. Ejection distance z as a function of applied voltage U_e

Measurements of the (Q/m) parameter

The parameter measurements were carried out in the system as in Figure 8. As voltmeter Electrometer RFT 6305 was used. Total capacitance (including cup and cables) was C_T= 13.25 nF.

The metal pipe was 800 mm over the bottom of Faraday cup. Just like before charge was applied to the metal pipe and soap bubble. After the bubble slips from pipe the voltage was immanently turned off, so as not to disturb the measurements.

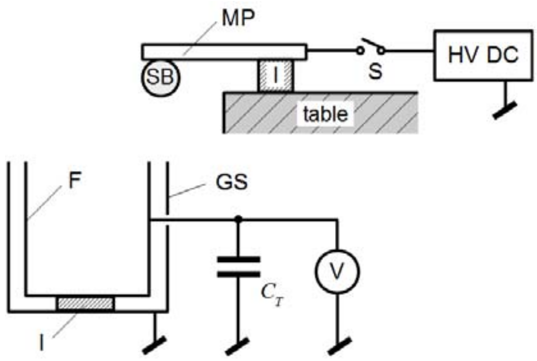

Fig.8. Setup for soap bubble charge measurement, GS – grounded shield, F – Faraday cup, SB – soap bubble, S – mechanical switch, MP – metal pipe, HV DC – DC high voltage supply, I – insulating supports

It should be noted that field distribution (including its values) for setup shown in Figure 8 can differ significantly from that for setup shown in Figure 3.

Charge of single bubble Q as a function of applied charging voltage U_e is shown in figure 9.

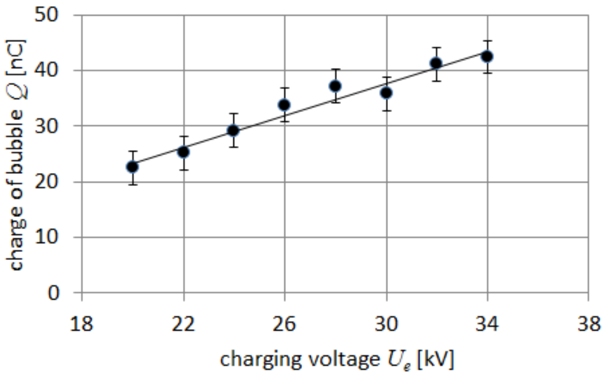

Fig.9. The charge of single soap bubble Q as a function of charging voltage U_e

The measured bubble charge Q increases linearly with increase of charging voltage U_e, with no observed signs of charge saturation. For voltages U_e in the range 26–34 kV more bubbles landed on the grounded shield than inside the cup. This suggests that the parameter (Q/m) should be greater than 2 mC/kg. In few cases, the charged bubble while sliding from pipe splits itself into two bubbles floating in opposite directions. If applied voltage was greater than 34 kV the bubble burst almost immediately. These observations lead to the conclusion that the charge Q on bubble should be close to Rayleigh limit. The maximum measured the charge on the single bubble was Q = 45nC which is 82% of calculated Rayleigh limit for a bubble with 25 mm radius. That confirms conclusion, based on observations, that the bubble charge was near the Rayleigh limit.

In order to estimate the value of the (Q/m) parameter measured charge Q was divided by each of 3 masses (from earlier measurements see section 3) – maximum (m_b = 24 mg), average (m_b = 13 mg), and minimum (m_b = 9 mg) measured mass. The results are shown in Figure 10.

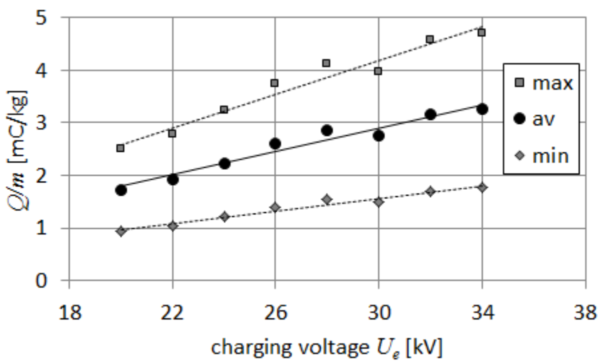

Fig.10. Parameter (Q/m) of single soap bubble as a function of charging voltage U_e for extremes and average mass values. “max” = maximum (Q/m) value calculated for minimal mass m_b = 9 mg, “av” - average (Q/m) value, “min” = minimum (Q/m) value for maximum mass m_b = 24 mg

Obtained values of the (Q/m) were on the level of 1.8–4.8 mC/kg which matches the predictions made in section 3 (taking into account real bubble mass). They were however much more lower than anticipated 12 mC/kg (section 2).

It can be seen that assuming the maximum bubble mass the (Q/m) parameter does not satisfy the condition 2 mC/kg, required to recognize electrification as effective. An additional experiment for demonstrating the dominance of electrostatic force acting on a single bubble was provided.

Below the pipe, a metal electrode (600 mm high, 400 mm wide) was placed perpendicular to the floor. The electrode was placed at distance d from the spot where bubble falls naturally due to gravitational force i.e. directly below pipe - as shown in Figure 11. During tests constant voltage U_e = 26 kV was applied (so that the produced bubbles will be stable).

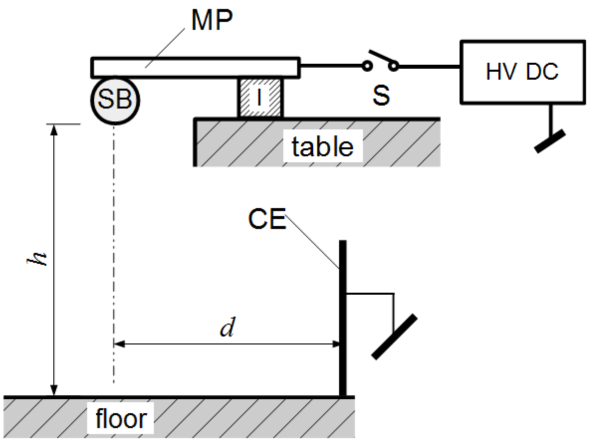

Fig.11. Setup for observing charged bubbles trajectory, CE – collecting electrode, h = 800 mm

Percentage of bubbles p reaching the electrode CE as a function of distance d is shown in Figure 12.

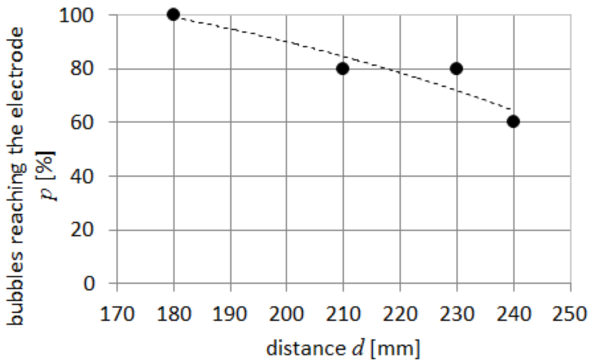

Fig.12. Percentage of bubbles p reaching the electrode as a function of distance d

In most cases, the bubbles landed in the middle of the electrode CE, 200–400 mm above the floor. It should be noted that Figure 12 shows the percentage of the bubbles that touched grounded electrode CE, but trajectories of all bubbles were affected and curved towards the grounded electrode CE. This means that the electric field has a significant influence on the trajectory of the bubbles, which suggests that the obtained values (Q/m) were higher than 2 mC/kg.

Summary and future works

- the maximum value of the parameter (Q/m) obtained was at the level of 2–5 mC/kg. The maximum charge obtained on the single bubble was close to the charge calculated from the Rayleigh limit. It should be possible to obtain higher values (Q/m) by producing much lighter bubbles, what should be possible according to the literature review,
- there was a clear difference in the trajectory between electrified bubbles and neutral ones, so the (Q/m) value is enough to ensure the dominance of electrostatic force,
- future works should focus on:
  - o producing lighter bubbles with a constant mass and diameter,
  - o developing a method of producing a reproducible aerosol, characterized by small nanometric droplets, from bursting bubbles,
  - o developing the system for simultaneous measurement of the bubble charge and mass of in order to unambiguously determine the parameter (Q/m) value,
  - o optimization of the electrification process, i.e. obtaining maximum possible values of (Q/m) at voltages significantly lower than those presented in this paper.

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