Ascent Velocity of Plasmoids Generated by Surface Discharges

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(Received 6 July 2009 / Accepted 27 August 2009)

The ascent velocity of long-lived plasmoids generated under atmospheric conditions to simulate ball lightning was estimated in [Fussmann *et al.*, Phys. Unserer Zeit **39**, 246 (2008) and Jegorov *et al.*, Tech. Phys. **53**, 688 (2008): Refs. 1 and 2 in the text, respectively], using a rigid sphere model with poor agreement with the experiment. The plasmoids were, however, deformed. Much better agreement is obtained using the Davies and Taylor formula, which describes the ascent velocity of large spherical-cap bubbles.

Keywords: ball lightning, plasmoid, ascent velocity, buoyancy

DOI: 10.1585/pfr.4.046

Recently, laboratory experiments were performed in which long-lived plasmoids were generated under atmospheric conditions [2–5]. These plasmoids are considered to be suitable for explaining the phenomenon of ball lightning. In the experiments, 0.1 g of water was evaporated and partly ionized by a surface discharge in the water. Plasmoids with a maximum diameter of up to 0.2 m rose through the atmosphere because of the buoyancy effect. After the discharge phase of 0.1 s with energy input, the plasmoid existed for further 0.15 s without energy input. The maximum lifetime was 0.25 s [3] and 0.5 s [2, 4]. An even a longer lifetime of up to 1.2 s could be achieved using carbon aerosols instead of water [2]. The ascent velocity in the experiments was 0.8 - 1 m/s [2, 3], so a plasmoid could rise up to 1 m.

The simplest estimation of the ascent velocity can be performed assuming a spherical plasmoid with density ρ, volume V, and radius r. The forces acting on the plasmoid are given by

Gravitation

$$F_\mathrm{G} = \rho g V$$

Buoyancy

$$F_\mathrm{B} = \rho_\mathrm{air} g V$$

Drag force

$$F_\mathrm{D} = 0.5 c_\mathrm{D} \pi r^2 \rho_\mathrm{air} v^2.$$

Here, v is the velocity of the plasmoid, g is the Earth's gravitational acceleration, and c_D is the drag coefficient. From the force balance $F_\mathrm{D} + F_\mathrm{G} = F_\mathrm{B}$, we find the following expression for the ascent velocity:

$$v = \sqrt{\frac{8rg}{3c_\mathrm{D}}(1 - \frac{\rho}{\rho_\mathrm{air}})}.$$

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The density of the plasmoid was determined experimentally. The water loss from the source measured by weighing was 0.1 g in every discharge. With a volume of about $10^3\,\mathrm{cm}^3$, the density is $10^{-4}\,\mathrm{g/cm}^3$ and thus much smaller than the density of the surrounding air ($1.2 \times 10^{-3}\,\mathrm{g/cm}^3$). For $\rho \ll \rho_\mathrm{air}$ the expression for the ascent velocity simplifies to

$$v = \sqrt{\frac{8rg}{3c_\mathrm{D}}}.$$

With the drag coefficient for a sphere $c_\mathrm{D} = 0.47$ (see Table 7.1 in [6]), an experimental value for the radius of a spherical plasmoid $r = 0.06\,\mathrm{m}$ (see Fig. 3 in [3]), and $g = 9.81\,\mathrm{m/s}^2$, the ascent velocity is 1.8 m/s. This value is 2.3 times the experimental value of 0.8 m/s given in [3]. Consequently, the presented model cannot explain the observed ascent velocities.

In [2], a similar result was obtained using a rigid-sphere model. The authors tried to improve the agreement with the experiment by giving up the condition $\rho \ll \rho_\mathrm{air}$. They increased the density in the plasmoid to match the experimental value of the ascent velocity. The result was that a spherical gaseous water ball with a diameter of 0.14 m must have a density corresponding to a temperature of 320 K. This conclusion is in contrast to the temperature measurements in [3], where core temperatures of about 3000 K were found. Thus, even the unphysical increase in the density of the plasmoid cannot explain the observed velocity within the frame of the rigid sphere model.

The shape of a plasmoid depends on the experimental conditions. After [2], various forms are possible in the generation process. By varying the electrode size and the discharge parameter, spherical plasmoids can be generated. However, ascending plasmoids are deformed; see Fig. 4 in [4], Fig. 1 in [5], or the schematic in Fig. 1 in [2]. This is especially the case for large plasmoids, because the surface tension loses importance with increasing size.

We now consider the ascent of gaseous bubbles in a liquid. Depending on the size of the bubble, three different geometrical shapes are possible: a) spherical b) ellipsoidal and c) spherical-cap. For air in tap water at 20°C, bubbles with volume-equivalent diameters $d_e > 0.01$ m have the spherical-cap shape. For these bubbles, the ascent velocity is described by the formula of Davies and Taylor [7]:

$$v = \frac{2}{3}\sqrt{ga(1 - \frac{\rho_{\mathrm{air}}}{\rho_{\mathrm{water}}})}.$$

Here, a is the curvature radius of the spherical cap. The Davies and Taylor formula was derived from the Bernoulli theorem. The only assumption is the spherical shape of the front. The equation is experimentally confirmed in the range $a = 0.015$ - 0.1 m (see Fig. 8.2 in [8]). Because $\rho_{\mathrm{water}} \gg \rho_{\mathrm{air}}$, the factor in parentheses is 1 and can be omitted in our case.

Often the Davies and Taylor formula is written for the volume-equivalent diameter of a sphere d_e [8, 9],

$$v = 0.711\sqrt{gd_e}.$$

The ratio between a and d_e is given by

$$\frac{a}{d_e} = [2j(\theta_w)]^{-1/3}$$

with the function

$$j(\theta_w) = 2 - 3\cos(\theta_w) + \cos^3(\theta_w).$$

The angle θ_w is extended by the base of the spherical cap. For large Reynolds numbers, $\theta_w = 50°$. For this angle, the values $j(50°) = 0.337$ and $a/d_e = 1.14$ hold.

We now apply the formula of Davies and Taylor to the plasmoids shown in Fig. 3 of [3]. The spherical plasmoid has a diameter $d_e = 0.12$ m. The spherical radius of a volume-equivalent spherical-cap plasmoid is calculated to $a = 0.14$ m. The right part of the Fig. 3 in [3] shows a deformed plasmoid which can be approximated by a spherical cap of this radius. Using these values, we arrive at an ascent velocity of 0.8 m/s, which agrees well with the experiment. Note that the radius of the spherical-cap plasmoid, $a = 0.14$ m, is already outside the experimentally validated range of the Davies and Taylor formula.

The term ball lightning suggests the topological form of a sphere. In the laboratory experiments, however, the transition of a spherical-cap plasmoid into a toroidal plasmoid was experimentally observed [2, 3]. For smaller plasmoids, the spherical-cap form was stable. The size of a plasmoid depended on the deposited power [4]. A detailed experimental study of the maximum possible size of a spherical or a spherical-cap plasmoid does not exist.

Large gas bubbles rising under the effect of buoyancy are known to either adopt a spherical-cap shape or undergo a topological transition after which they become toroidal. The maximum air bubble size in water was determined experimentally. In [10], the experiments of Temperley and Chambers were cited. Temperley and Chambers generated large spherical-cap bubbles with a radius up to $a = 0.15$ m which corresponds to a sphere with an equivalent diameter of $d_e = 0.13$ m and a volume of 1150 cm^3, respectively. Davies and Taylor were able to produce spherical-cap bubbles with a volume up to 200 cm^3 corresponding to an equivalent diameter of $d_e = 0.072$ m. In general, the maximum size of a spherical-cap bubble depends on the initial conditions of the generation.

On the other hand, the size of ball lightning may be approximated by numerous observations [11]. Ball lightning is described as an orange or white sphere with a diameter of 0.2 to 1.0 m. Thus, it is a very interesting question whether such large and stable spherical or spherical-cap plasmoids can be generated in the laboratory.

Acknowledgment

This study was conducted during a visit to the University of Nagoya. The author is grateful to Prof. Takamura and Prof. Ohno for stimulating discussions.

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