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Droplet Cloud Formation upon Disintegration of Free-Falling Water Ball

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Abstract—Free fall of an approximately spherical water ball with a volume within 0.1–0.5 l from the state of rest at an altitude of up to ~5 m was experimentally studied. The deformation of the liquid ball under the action of aerodynamic forces and instabilities leads to its disintegration with the formation of a droplet cloud with rapidly growing dimensions in both longitudinal (vertical) and lateral directions.

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The patented method [1] of extinguishing forest fires stipulates the use of envelope-free water projectiles accelerated under the action of combustion and/or detonation products of inflammable gas mixtures with air or oxygen. Rough estimations show that it is principally possible to create devices of the gun type that are capable of accelerating in a pulsed regime large (virtually unlimited) masses of water up to velocities on an order of several dozen meters per second and throwing them to distances within several dozen meters. In this context, it was of interest to study the specific features of propagation of envelope-free water projectiles of rather large mass in air.

Previously, Magarvey and Taylor [2] presented the results of experiments with free-falling water drops with a diameter of about 1.5 cm (and, hence, a volume of about 1.8 cm@3) from an altitude of up to ~5 m. During the flight, a water drop transformed into an oblate disk under the action of pressure distributed over its surface (increased pressure at the poles and decreased on the side surfaces). Then, the flat projectile acquired a parachute-like canopy shape, strongly expanded, and fractured as a result of thinning with the formation of a cloud of small drops.

It is a common knowledge that typical raindrops have a size rarely exceeding 5–6 mm and possess a characteristic (droplike) shape. This stable shape is explained by the balance of aerodynamic forces that deform the drop) and surface tension that counteract the deformation). As the drop size increases, the balance is violated in favor of the aerodynamic forces and the drop exhibits disintegration according to a scenario described in [2]. It was reported [2] that this scenario is stably reproduced for drops with diameters of 20 mm and above, while possessing a probabilistic character for smaller drops.

This Letter presents the results of experiments analogous to those reported in [2], but with drop volumes increased to within 0.1–0.5 l, so that these drops should more adequately be called cannonballs (balls). A water ball of nearly spherical shape with a volume of up to 0.5 l was created by fracturing a rubber envelope that was strongly extended by the water it contained. Each envelope (medicinal latex finger cot) was initially fixed on the end of a cylindrical textolite holder with an axial water-supply channel that also contained and guided a steel needle. After filling the latex envelope with water and raising the assembly to a preset altitude, the needle was driven to perforate the envelope at the bottom point. The fragments of a strongly extended envelope contract and slide away over the surface of the water ball for a period of time within several milliseconds.

The free fall of a released water ball and its transformation was monitored by a Cassio Exilim EX-F1 digital camera operating in video mode at a rate of 300 shots per second. In each experimental run, the video monitoring was performed with a certain interval of distances (e.g., 0–1, 1.4–2.0, and 3.9–5 m) from the start (bottom point of a ball in the initial position).

Figure 1 shows two shots of a video record, which illustrate different stages of water ball transformation during its free fall from an initial altitude of ~5 m. We carried out a total of about twenty experiments. In most cases, the initial ball shape was rather irregular, since it is distorted by the motion of latex envelope fragments upon perforation. For this reason, photographs in Fig. 1 show the results of various experiments with balls of different initial volumes, which possessed the most regular initial spherical shapes. The data in each photograph indicate the distance X traveled by the front of the ball (measured from the bottom point

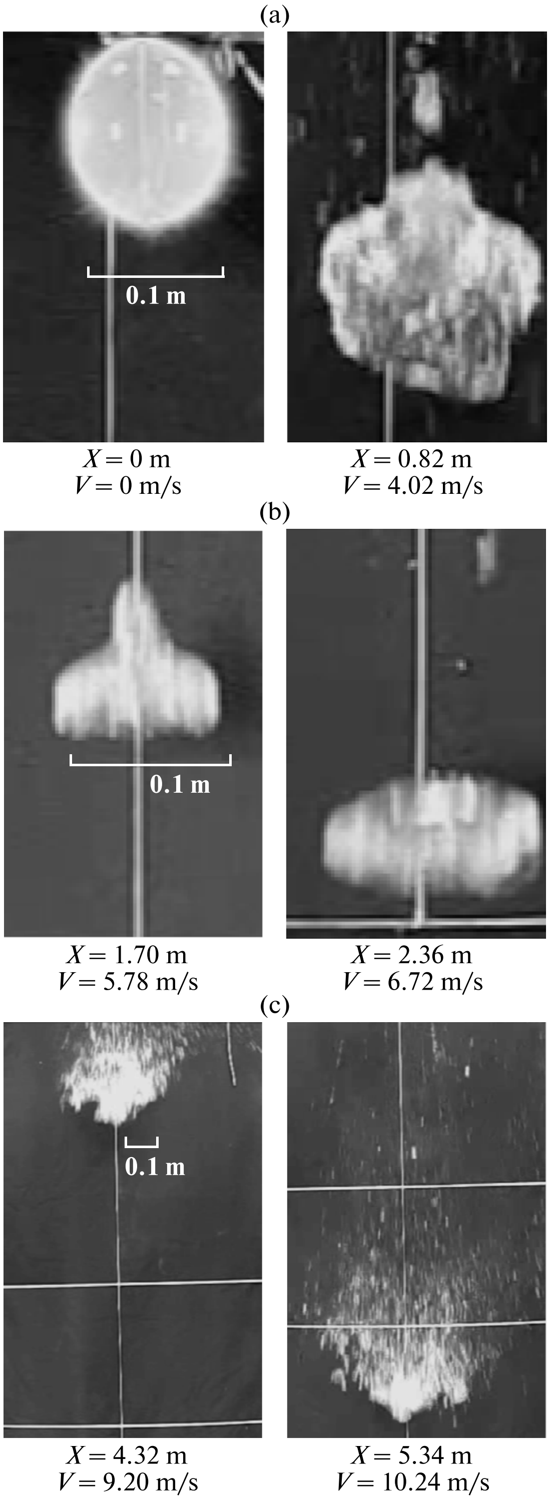


Fig. 1. Photographs showing deformation and disintegration of water ball during its free fall in air from an initial altitude of ~5 m: (a) 0.5-l ball, $X = 0–0.8$ m; (b) 0.1-l ball, $X = 1.7–2.4$ m; (c) 0.2-l ball, $X = 4.3–5.3$ m.

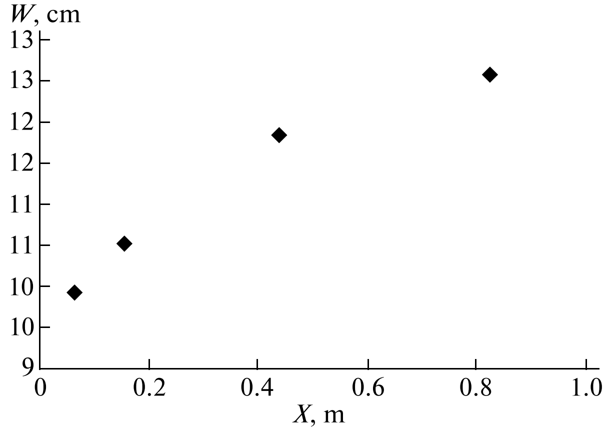
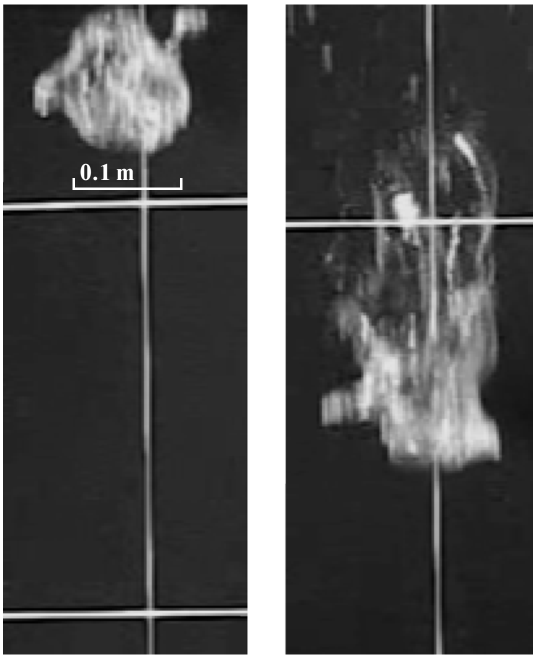


Fig. 2. Plot of transverse (lateral) size W versus traveled distance X for free-falling water ball with an initial volume of 0.5 l.

of the ball in the initial position) and its velocity V. For each distance X, the flight time t and velocity V can be estimated using the elementary formulas as $t = (2X/g)^{1/2}$ and $V = (2gX)^{1/2}$, where g is the acceleration of gravity.

Even the very initial stage of free fall showed deformation of the ball, which had an approximately spherical initial shape (Fig. 1a). The action of air counterflow produces a certain distribution of pressure over the ball surface, which is increased at the poles and decreased at the equator. As a result, the ball exhibits flattening in the vertical direction and, as a whole, becomes oblate (Fig. 2.) At the same time, perturbations appear and grow on the bottom surface of the ball. This process is probably explained by the development of Rayleigh–Taylor instability [3], which can be operative for a short period of time (within several milliseconds), whereby the fractured latex envelope released the lower part of the ball but still holds its sides. The initial perturbations are caused by the tangential pressure of residual latex on the ball surface. When the water ball is completely released and starts to free fall (zero-gravity state), the Rayleigh–Taylor instability ceases to develop, but the related initial perturbation of the bottom surface continues to develop as a result of inertia.

At a later stage of free fall (Fig. 1b), the deformation continues and the ball acquires a disk shape with a loose structure. The loose structure formation proceeds by a mechanism analogous to that observed in [2], whereby the development of instabilities on the bottom surface of the free-falling disk leads to the appearance of channels penetrating through the bulk of water. This conclusion is confirmed by the results of experiments (Fig. 3) in which an expanding parachute-like canopy (similar to that reported in [2]) was formed. On reaching a certain critical size, the expanded ball bursts with the formation of a cloud of small droplets moving in all directions. This mechanism of free-falling ball disintegration was repeatedly reproduced in our experiments.



$X = 1.41$ m
$V = 5.27$ m/s

$X = 1.98$ m
$V = 6.24$ m/s

Fig. 3. Photographs showing formation of loose expanding body and its disintegration during free fall of a 0.2-l water ball.

The joint action of the aforementioned factors (deformation of a ball and instability of its bottom surface) leads to disintegration of the ball and the formation of a cloud of fine droplets (Fig. 1c). The droplet cloud takes the shape of a cone oriented with its vertex downward. The characteristic size of a cloud formed from a 0.2-l ball reaches ~0.5 m and continues to grow in both longitudinal (vertical) and transverse (lateral) directions.

It can be suggested that, as the size of the water ball (and its initial shape) is increased, the above experimentally observed laws would still be operative and larger balls will also transform into droplet clouds. This hypothesis refers not only to free-falling balls, but also to any other flight of a water ball in the atmosphere. The same laws may govern the subsequent development of a droplet cloud. Indeed, the cloud is retarded by air, so that the acceleration is directed from light air to a heavier droplet cloud, which corresponds to conditions for the onset and development of the Rayleigh–Taylor instability. The development of this instability at the boundary of a flying cloud of dispersed medium was observed in experiment [4].

In conclusion, we have developed a method and conducted a series of experiment with a free fall of spherical water balls with initial volumes up to 0.5 l. The ball exhibits a tendency to flattening under the action of aerodynamic forces from the very beginning of free fall and rapidly transforms into a disk with increasing diameter. At the same time, instability develops on the bottom surface of the disk. The simultaneous action of these factors leads to the complete disintegration of the water ball with the formation of a droplet cloud, which rapidly grows in both the longitudinal (vertical) and transverse (lateral) directions.

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