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Investigation of the Spray Generation due to Bag Breakup Fragmentation Phenomena with Optical Methods in Environmental and Technical Systems

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Abstract

This paper discusses the results of a detailed study of bag breakup spray fragmentation process obtained using various panoramic optical methods: shadow imaging and laser-induced fluorescence (LIF) with high-speed video recording. The experiments were carried out in two fundamentally different configurations. When blowing the air flow above a deep-water layer, with the presence of large-scale waves on the surface, and vice versa in conditions of thin layers of liquid. Comparison of the results of observations demonstrated not only the general similarity of the evolution scenario, but also the dependences of the spatiotemporal scales of the process of fragmentation and the formation of droplets on the characteristic flow velocities according to the bag breakup events. This indicates the universal nature of the phenomena leading to the fragmentation and separation of drops from the surface of a liquid blown by a gas flow in natural and technical hydrodynamic systems of a wide class with scales varying over a wide range.

Keywords: droplets, fragmentation, thin films, laboratory modeling, shadow method, LIF, high speed filming.

1. Introduction

The mechanism of fragmentation of liquid elements (individual drops or jets) according to the bag breakup type (when canopy of a thin film with a thickened rim are formed, followed by rupture and formation of drops) in co-current gas flows was described quite a long time ago (see, for example, review [1]). It was shown that it is observed in the range of Weber number change (We= $\rho V^2 d/\sigma$, ρ is the liquid density, V is the gas flow velocity relative to the drop, d is the drop diameter, σ is the surface tension coefficient) from 12 to 50. These regimes for example for water at room temperature can be observed for drops from 100 μm to 10 mm, at air velocities from 10 cm/s to 100 m/s. So, we are talking about fairly common conditions of multiphase flows, both in technical and natural systems. However, as shown by later works [2–5], this process is typical of the fragmentation of the free surface of a liquid layer under the action of the gas flow in various technical and natural systems. The most typical representatives of the former are thin-layer liquid flows blown by gas flows, which are realized, for example, in pipes of power plants under conditions of interphase transitions (vapor condensation). A striking example of natural systems where these phenomena are observed (for the first time in [6]) is the interaction of air flows of the turbulent boundary layer of the atmosphere with the surface of hydrosphere objects, and primarily the world ocean. As was demonstrated in [7], the bag breakup mechanism is dominant and, accordingly, the spray generation function for sea aerosol was constructed on its basis (see [8]). Thus, we are dealing with systems of fundamentally different characteristic spatial scales. However, in order to develop a general theory that would make it possible not only qualitatively but quantitatively to describe these phenomena in different systems, it was necessary to obtain and compare their spatiotemporal characteristics. In this work, we first estimated the parameters of bag breakup events formed in experiments on modeling wind-wave interaction in laboratory conditions. Then, the results of studies of the flows of thin films blown by gas in pipes were analyzed. Panoramic optical methods were used in both experiments.

2. Scheme of experiment PIV-method use.

A series of experiments was carried out on the High-Speed Wind Wave Flume (HSWWF) of the Institute of Applied Physics, Russian Academy of Sciences, aimed at a detailed study of the phenomena of fragmentation of the surface of a deep liquid layer under the air flow action in the frame work of laboratory modeling of the processes of generation of sea aerosol during wind wave interaction. The scheme of experiments (see Fig. 1) and measurements was similar to that previously used in [7].

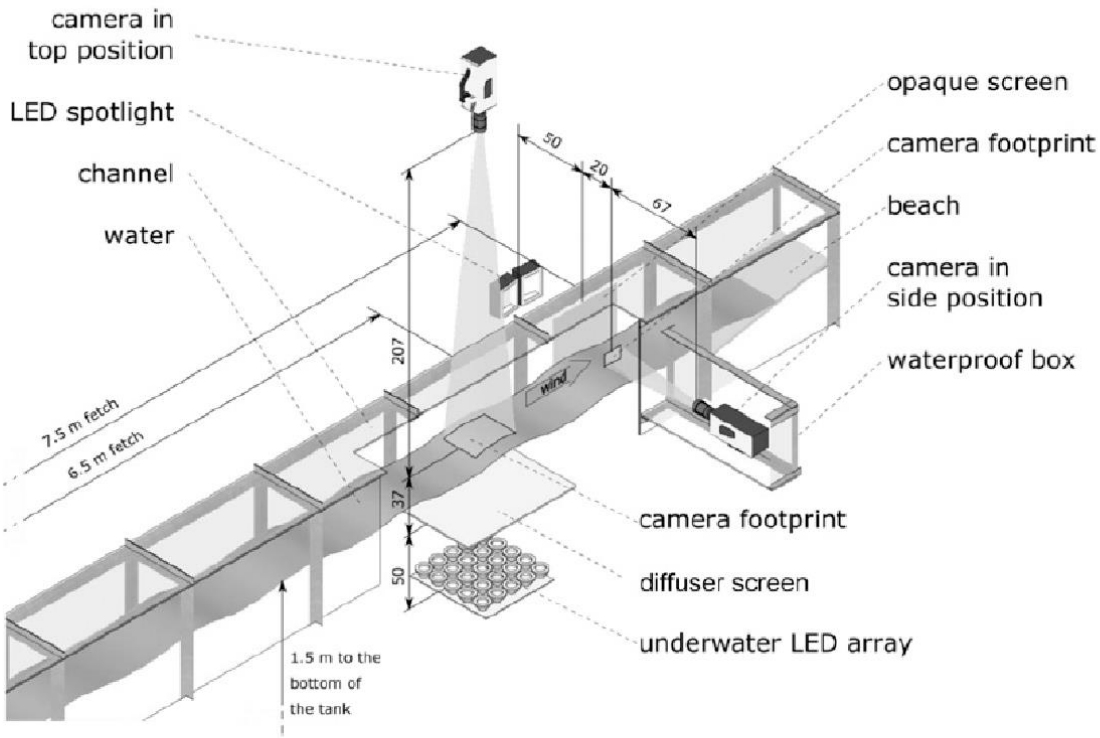
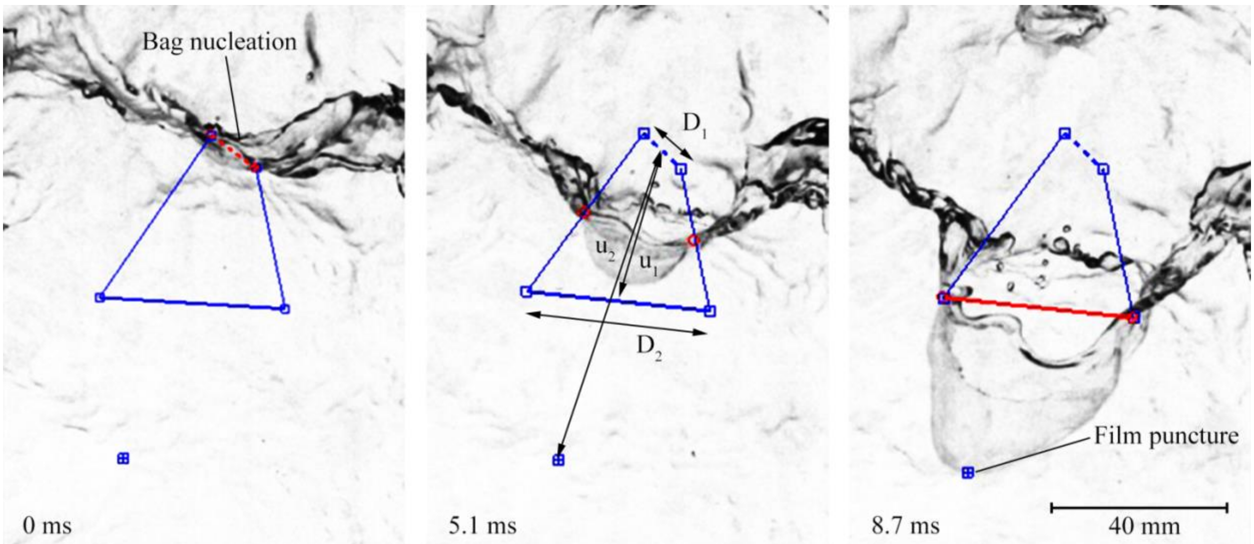


Fig. 1. Schematic diagram of experiment on the investigation of droplets formation on the deep-water layer under the air flow action on the HSWWF

The range of velocity change on the axis of the aerodynamic channel with a cross section of 0.4×0.4 m, installed above the free water surface with a depth of 1.5 m, ranged from 16 to 25 m/s. At the same time, the equivalent wind speed U_{10}, recalculated to the height of standard meteorological measurements of 10 m according to the logarithmic law of the turbulent boundary layer, varied in the range from 22 to 40 m/s. Thus, various regimes of the wind-wave conditions were realized, including regular collapse with the formation of droplets. To study the events leading to the generation of droplets, high-speed video recording of the side and top view of the rough water surface was performed. The side view provided good qualitative information, however, due to the three-dimensional nature of the breaking wave crests, it did not allow the identification of most events and the study of their characteristics. The main information was obtained on the basis of the analysis of images taken from above. In this case, a shadow imaging method was used with illumination from under the water using an array of powerful LED lamps located under opaque screen. The filming was performed by a high-speed NAC HX-3 camera, at a speed of 4500 fps and a shutter speed of 50 μs. The taking area was 31×24 cm, with a resolution of 1632×1280 pixels. Thus, in comparison with the experiments in [7], the spatial resolution was significantly increased for the purpose of subsequent detailed processing of the acquired images. The number of entries varied depending on the set airflow rate. At low winds, for the weakly breaking waves, corresponding low rate of droplets production more records were required to obtain an ensemble of realizations comparable in size to the conditions for high winds. A total of 50 recordings of 32796 frames were made.

Processing was carried out using specially developed software. It was used to mark bag breakup events during the entire process of its evolution (from inception to rupture of the canopy). An example of processing a sequence of frame fragments is shown in Fig. 2. Based on the marking results for each bag breakup phenomenon, the following were determined: the initial size of the perturbation from which the canopy is formed, defined as the distance between the edge markers in the D_1 frame; the final size of the canopy D_2, defined as the distance between the edge markers in the frame where the film rupture is detected; duration time - from the moment of the beginning of the formation of the canopy until the moment of its rupture τ. The velocities of the edges and the center of the canopy u_1 and u_2 were calculated as the distance between the respective midpoints of the edge markers or centers of the canopy on the initial and final frames, divided by τ. In this case, the markup was often carried out in a reverse sequence in time. The reason for this was that it was easier to first fix the moment of canopy rupture, and then, by analyzing the previous frames, try to determine the moment of birth and estimate, among other things, the initial size.



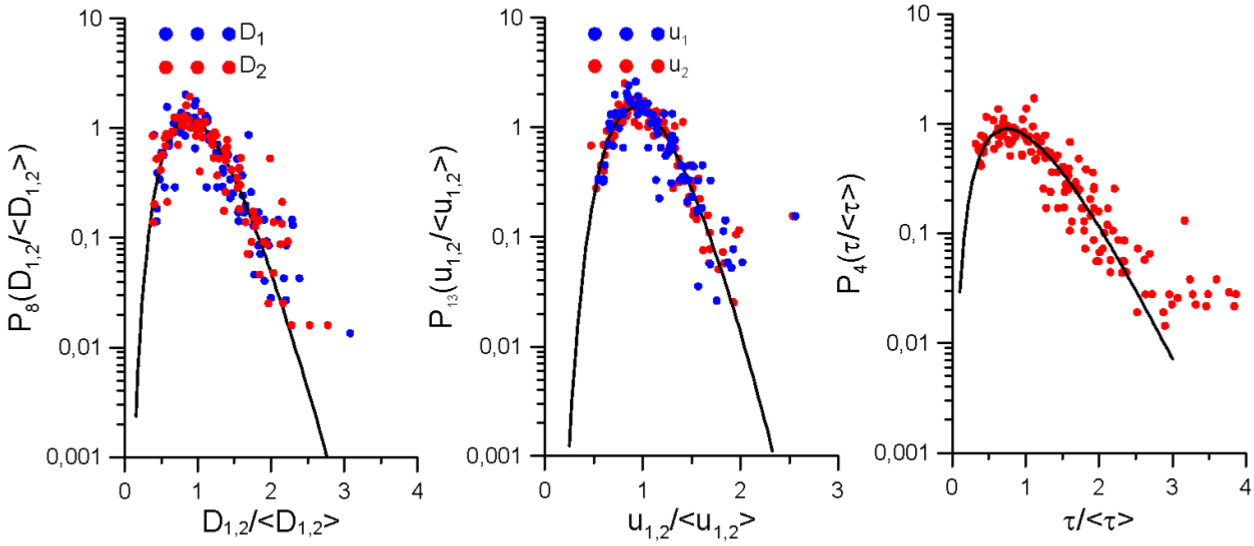
(a) (b) (c)

Fig. 2. An example of processing a sequence of frames to determine the characteristics of bag breakup event on image fragments: a) initial frame (the birth); b) intermediate frame with boundary marks; c) the last frame in the sequence at the moment of membrane film rupture.

The distributions of the bag breakup phenomena described above were obtained (Fig. 3). They were approximated by Gamma function:

$$P_n(x) = \frac{n^n}{\Gamma(n)} x^{n-1} e^{-nx} \quad (1)$$

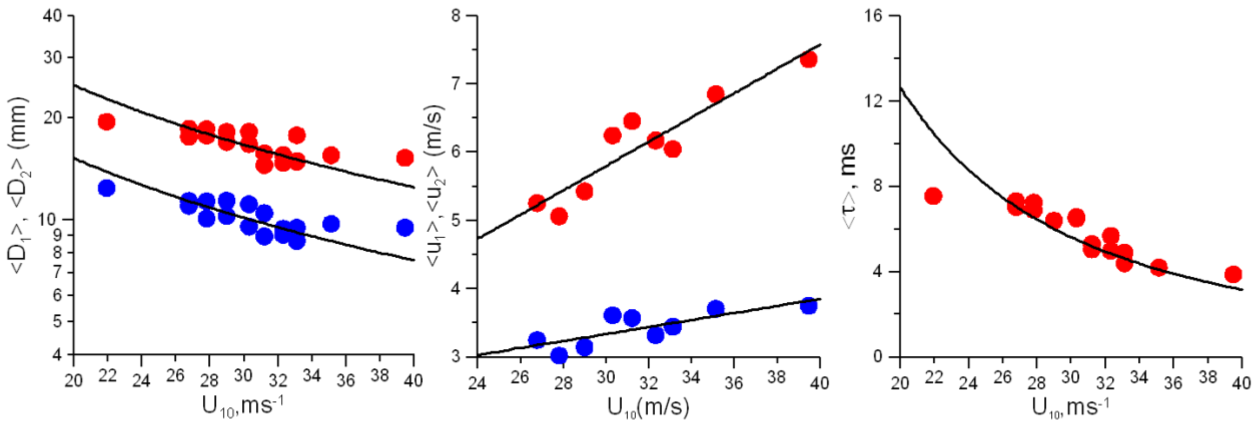
with the following indicators n: for sizes D_1 and D_2, n=8; for speeds u_1 and u_2, n=13; for lifetime τ, n=4.



(a) (b) (c)

Fig. 3. The distributions normalized on the average a) initial D_1 and final D_2 sizes of the canopy, b) velocities of the edges and the center of the canopy u_1 and u_2, c) lifetime τ

Obtained average values are presented as a function of the equivalent wind speed U_{10} on the Fig 4.



(a) (b) (c)

Fig. 4. Dependences of the average values of the characteristics of bag breakup phenomena on the U_{10}: a) initial (blue) and final (red) size; b – velocities of the edges (blue) and the center of the canopy (red); c - lifetime. Lines show power-law approximations

The following power-law approximations have been proposed:

$$\langle D_1\rangle = 3*10^2/U_{10} \tag{2}$$

$$\langle D_2\rangle = 5*10^2/U_{10} \tag{3}$$

$$\langle u_1\rangle = 1.8 + 0.05*U_{10} \tag{4}$$

$$\langle u_2\rangle = 0.46 + 0.168*U_{10} \tag{5}$$

$$\langle \tau\rangle = 3*10^2/U_{10}^{\ 2} \tag{6}$$

It can be seen that with an increase in the speed of the air flow, the size of the canopy and the lifetime decreases, and the velocities of inflation of the canopy increases.

3. Experiment to study processes of bag breakup fragmentation on the surface of thin liquid layer

Experiments to study the mechanisms of droplet tearing off by a gas flow from the surface of thin liquid layers were carried out in a horizontal channel of rectangular cross section (see Fig. 5). Channel length (x axis) 2000 mm, width W (y axis) - 161 mm, height L (z axis) - 25 mm. Water is supplied through a slotted gap to the bottom of the channel, where it is entrained along x by an air flow with a velocity Vg of 20 to 35 m/s. The liquid flow rate ranged from 1 to 5 cm/s. The height Reynolds number Re_L=q/Wν, determined through the variable flow rate q, varied in the course of experiments in the range from 110 to 520.

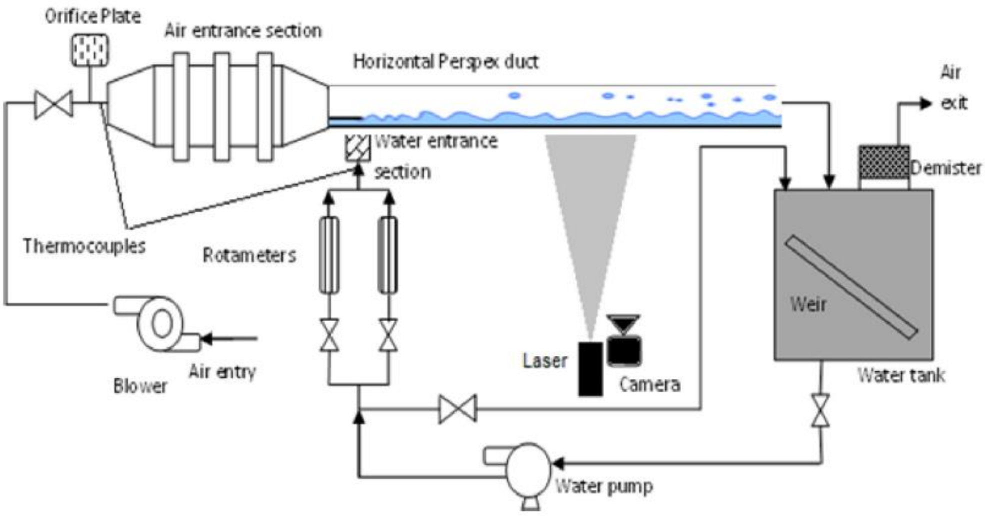


Fig. 5. Scheme of the experiment to study the processes of spray generation during the interaction of an air flow with a thin layer of water.

In contrast to the measurements under the conditions of a deep-water layer, described in the previous paragraph, the method of laser-induced fluorescence (LIF) was used here, which makes it possible to obtain a complete picture of the spatiotemporal distribution of the film thickness in the flow (details of the method application see in [9]). The measurements were taken at a distance of 1600 mm from the entrance to the channel using. A section of the channel bottom measuring 100 mm by 50 mm was illuminated from below, through the transparent bottom of the channel, by a laser beam scattered over the area. The beam was created by a pulsed laser with a wavelength of 527 nm. The laser light excites the fluorescent glow of rhodamine 6G dissolved in the water at a low concentration (15 mg/l). The induced illumination was recorded (also through the bottom of the channel) by a high-speed camera equipped with a light filter with a transmission wavelength of 550 nm. From the local instantaneous fluorescence brightness thus measured, using an appropriate calibration, it is possible to reconstruct the instantaneous local thickness of the liquid film. The described technique obtains data in the form of three-dimensional arrays of film thickness, $h(x,y,t)$, where t is time. The frame rate frequency is 10 kHz.

The Fig. 6 shows typical images of perturbation wave fronts on the surface of a liquid blown by a gas flow, on which horseshoe-shaped structures of a smaller scale are clearly visible, moving faster than the fronts. It is from these structures that bag breakup events are periodically induced (see Fig. 6). However, the multiple reflection of laser illumination from the thin film of the bag canopy, combined with the reflection from the thick film of the flow itself, leads to distortions in the obtained images, which are much more difficult to process compared to the shadow images in previous experiments. On the other hand, the sources of disturbances on the surface (waves of fast ripples) from which bag breakup events develop are well identified and can be marked to obtain quantitative information about them.

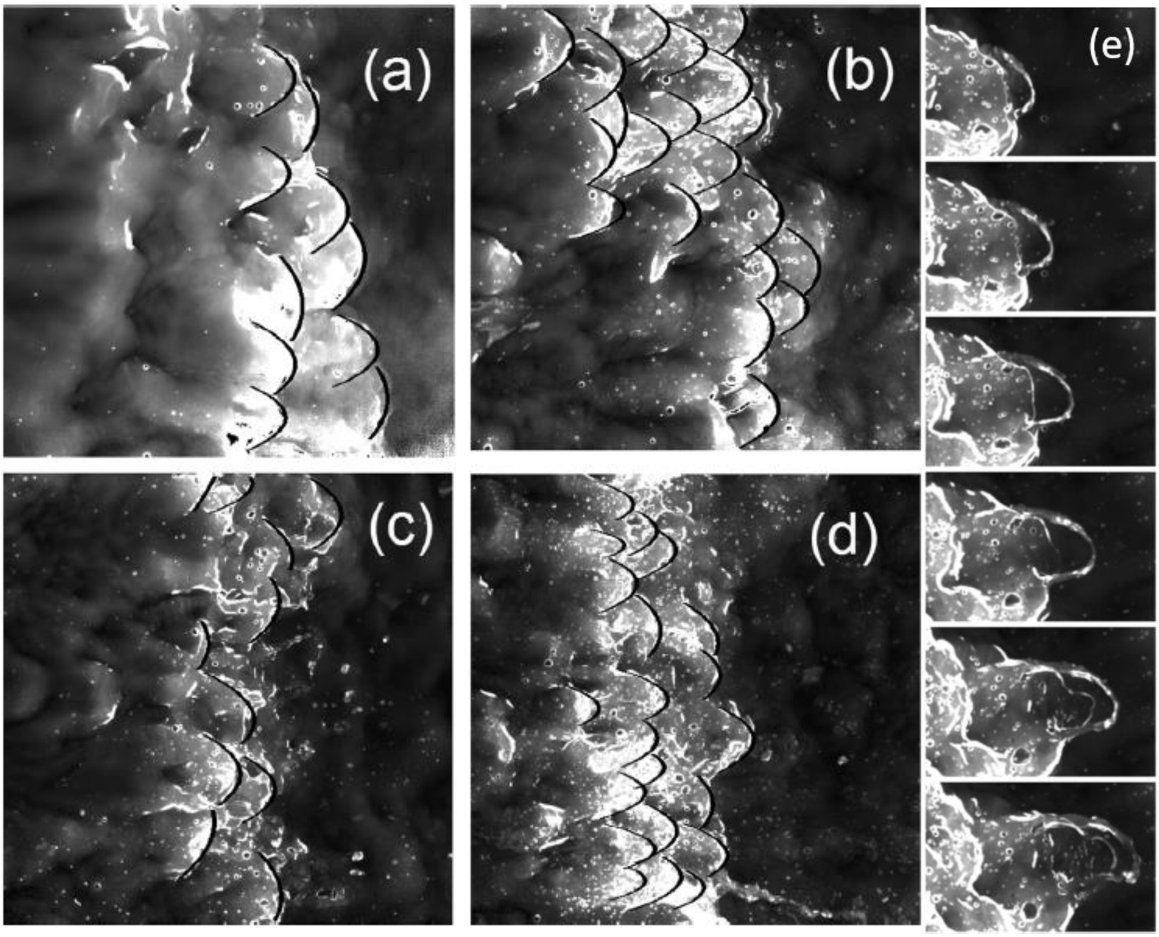


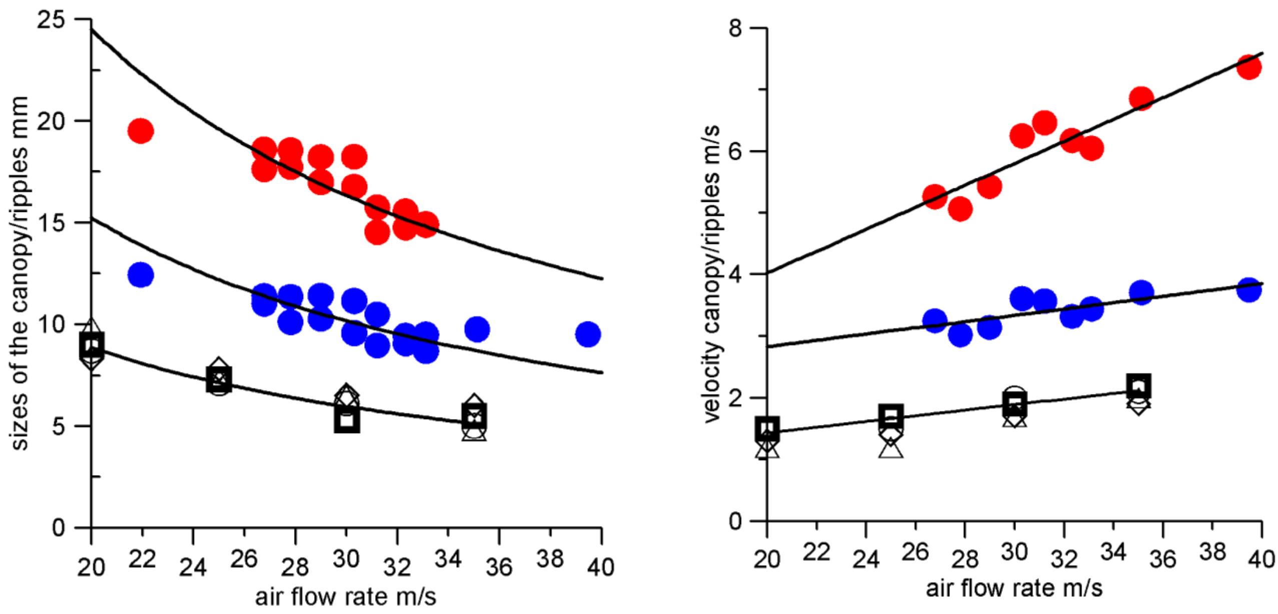
Fig 6. Left. Instantaneous images of fast ripples on the disturbance waves for different experimental conditions Re_L = 360, V_g = 20 m/s (a), 25 m/s (b), 30 m/s (c), 35 m/s (d). The size of the area is 50×50 mm. On the right, (e) shows a sequence of obtained images of a single phenomenon of the bag breakup for Re_L = 360, V_g = 30 m/s, area 20 × 13 mm; The interval between frames was 0.5 ms (an increase in time corresponds to downward).

Based on the results of processing images of fast ripple waves, it was possible to obtain distributions from which the average values of the width W_{fr} and their velocity V_{fr} were estimated. They were compared with previously found similar characteristics for the bag breakup themselves (in experiments on the deep water). The comparison of the results is shown in Fig. 7. It turned out that the dependence on Re_L is weak. At the same time, the power-law dependences for the sizez and velocities of the bag breakup event on the air flow rate U_{10} are well suited for describing similar dependences of the parameters of fast ripples on the V_g:

$$W_{fr}=1.7*10^2/V_g \quad (7)$$

$$V_{fr}= 0.51 +0.046*V_g. \quad (8)$$

It should be noted that the slope of the dependences for the boundaries of bags canopy u_1 and the velocity V_{fr} of fast ripple waves practically coincided (compare (4) and (7)), which in fact confirms that fast ripples are the disturbances which induced bag breakup events.



(a) (b)

Fig. 7 Comparison of average characteristics of bag breakup events in deep water and fast ripples on a thin layer of (a) sizes, (b) velocities. The red and blue circles are similar to the designations in Fig. 3. Black symbols correspond to different Re_L numbers (Δ - 155, ◇ - 220, ○ - 360, □ - 520).

4. Conclusion

In the course of the study, the behaviour of the scenario of fragmentation of the water surface and the bag breakup events of droplets generation was investigated for fundamentally different conditions for the interaction of a gas flow with a free liquid surface: a deep liquid layer with large-scale waves and a thin film with fast ripples on the surface. The first type of experiment was aimed at modelling the formation of marine aerosol during the interaction of wind with the sea surface in laboratory conditions. The shadow method with high-speed visualization was used. In turn, the processes of atomization of thin liquid films by a high-speed gas flow were studied using a laser-induced fluorescence method. In the first experiment, data were obtained on the characteristic dimensions and velocities of bag breakups, and in the second experiment, fast ripple (which are considered as seed disturbances from which bags can develop) were obtained. Despite the difference in the characteristic spatial scales of the systems, the dependences of the sizes and velocities of the bag breakup events and their seeds on the gas flow velocity turned out to be close to each other, which indicates the universality of the physical mechanisms that determine these phenomena in different systems.

Acknowledgments

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