Detailed investigation of bag-breakup process in the context of spray of droplets generation within wind-wave interaction

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Abstract. The main mechanism responsible for the generation of spume droplets in marine atmospheric boundary layer was investigated at the experiments carried out at the high-speed wind-wave flume of IAP RAS. Strong wind tears off water from the crest of the waves during bag breakup fragmentation of small-scale disturbances that arise at the air-water interface. Separate bag-breakup event forced to occur in a dried high-speed wind-wave flume was investigated qualitatively and quantitatively using multiperspective shadowgraph high-speed video recording.

1. Introduction

Recent studies of wind-wave interaction [1] have shown that bag-breakup fragmentation of small-scale disturbances that arise at the air-water interface under the strong wind the main mechanism responsible for the generation of spume droplets. This mechanism was first described in [2] where this mode of fragmentation of large drops in the lateral air flow, followed by the stage of inflating a large membrane, and its subsequent rupture into small drops was called “bag-breakup” mode. In [3], this mode was studied in more detail using high-speed video in a wide range of conditions, and in [4] a similar mode was observed when the jet fragmented in the transverse air flow. The existence of such a mode in natural conditions in nature was first demonstrated in [5], by the interaction of an air flow with rough water surface within the framework of laboratory modeling of the interaction of the atmosphere and the ocean on a wind-wave flume.

Sea sprays are typical element of the marine atmospheric boundary layer and important environmental effect. But there are significant uncertainties in estimations of sea sprays influence on the marine atmospheric boundary layer [6, 7] due to difficulties of direct measurements in hurricane conditions and insufficient knowledge about the mechanisms of the spume droplet's formation that leads to insufficient knowledge on the sea spray generation function, which characterizes the size distribution of droplets injected from a unit of surface in a unit of time. There is a difference in estimations of empirical function of spray generation by six orders of magnitude based on different observation reports (see a review of experimental data in [8]). Therefore, constructing the spray generation function as the basis for calculating the contribution of spray to exchange processes at the air-sea interface is one of the most important problems, we are trying to solve.

In our previous work [1] high-speed recordings of the water surface at high winds in controlled laboratory environment allowed us to retrieve the statistics of number of bag-breakup events appearing on the surface at various wind and water conditions. But to build the spray generation function as
convolution of the of single "bag" generation function and of the distribution function of droplets from one "bag-breakup", we need to know what droplets are formed during one bag-breakup fragmentation.

The second part of the article is devoted to the description of the methodology of experiments at high-speed wind-wave flume. We develop methods of creating a single "bag" and obtaining this distribution: due to spontaneous characterization of their occurrence on free water surface that complicated detailed studies the separate bag-breakup event was forced to occur in a dried high-speed wind-wave flume. The third part describes how high-speed video recordings of "bags" were captured using the shadowgraph technique. The fourth part is dedicated to processing by modified particle tracking techniques of high-speed image sequences of singles bag-breakup event to obtain a spray characteristic.

2. Experimental setup
The experiments were carried out in controlled laboratory environment on the High-speed wind-wave flume (HWWF) of the Institute of Applied Physics (IAP RAS). The operating cross section of the airflow is the flume was 0.4×0.4 m², straight working part of 10 m. During the experiments axis air velocity in the flume varied from 10 to 17 m/s, that corresponds to 20-50 Hz frequency of centrifugal fan equipped with an electronic frequency converter. More details of the facility construction and parameters of air flow and surface waves are described in [9].

The principal scheme of the experimental setup is shown in figure 1. Bag-breakup event was forced to occur at a small reservoir installed at a distance of 7.5 m from the beginning of the working section. The flume was closed at its bottom with rigid plates at the water level used in previous experiments [1] to prevent spontaneous bag-breakup event appearing on free water surface for investigations of a separate bag-breakup event. The measured value of the surface tension was \( \sigma = (7.0\pm0.15)\times10^{-2} \) N/m.

Bag breakup developed from artificial initial disturbance that was created at the desired position using the underwater jet from a submerged nozzle placed in vertical orientation 1,5 cm under water surface. It is consisted of 5 nickel tubes 20×2 mm, lined up in a row in cross-wind direction to create elliptical leaf-like disturbance. In order to damp the disturbances on water surface around the nozzle a sheet of 20 mm thick foam rubber with a hole 30 mm in diameter was placed above it. The foam was additionally covered with a 2 mm cell size nylon net. Water supplied to the nozzle at a pressure of 3 bar through an electromagnetic valve, controlled by a microcontroller. This enabled us to synchronize the moment of disturbance creation with triggers of both top and size high-speed cameras.

The dependence of the shape of the initial disturbance on time was investigated using image processing of frames from the side camera captured without wind. Image processing showed that this system allowed to inject up to 2.5 ml of water in 20 ms time interval with good repeatability: comparison of successive initial disturbances showed the stability of their shape within 10% for height and diameter.

Figure 1. The cross-section of the high-speed wind-wave flume: 1 – LED lights, 2 – solid flat bottom, 3 – opaque screen, 4 – high-speed wind-wave flume, 5 – top high-speed camera, 6 – bag-breakup, 7 – semi-submerged box, 8 – high-speed camera, 9 – nozzle, 10 – reservoir with water, 11 – foam rubber in water, 12 – nylon mesh.
Experiments were performed for 5 fan rotation frequencies from 30 to 50 Hz with 5 Hz step, that corresponds to centerline wind speeds from 10 to 17 m/s. Wind velocity profiles were measured at the working section with reservoir by the profile method using the L-shaped Pitot tube on scanning device with the differential pressure transducer Baratron MKS 226A (the accuracy of 0.5% of full scale range, i.e., 3 cm/s). The profiles were measured in 1 to 20 cm height interval with continuously moving tube (1.1 mm/s vertical scanning speed). For each fixed wind parameters, at least five profiles were measured for subsequent averaging. Friction velocity $u^\ast$ and equivalent speed $U_{10}$ at a standard meteorological height of 10 m were obtained using profiling method with logarithmic approximation of bottom part of turbulent boundary layer. The scaling parameter for the air turbulent boundary layer flow above the water surface is the friction velocity, defined via vertical turbulent shear stress: $\tau = \rho_{\text{air}} u^\ast v^2$, where $\rho_{\text{air}}$ is the air density. The friction velocity, $u^\ast$, varied between 0.46 and 0.73 m/s; the equivalent wind speeds $U_{10}$ between 16 and 26 m/s, that corresponds to Beaufort number up to 10 in field conditions.

3. High-speed video recording setup with shadow illumination technique

High-speed video recording was used to investigate the details of the bag-breakup fragmentation both qualitatively and quantitatively. Records were made for all 5 different wind speeds (fan rotation frequencies of 30 to 50 Hz), 9 to 17 records of the bag-breakup were captured for each speed. Record was interrupted at the moment the last droplets escapes the imaging area. Shape and size of the initial disturbance were controlled before and after each series of record by recording the dynamics of the disturbance without wind.

High-speed recording was synchronously made from top and from side. Side recording was made with high-resolution NAC Memrecam HX-3 high-speed digital video camera in shadowgraph configuration: vertical opaque screen was placed at the opposite to the camera wall of the flume and was illuminated from behind with two 300 W LED light source. The camera was placed in horizontal position at a distance of 60 cm from the center of the flume. Resolution of 63 μm/px at the frame size of 2560×960 px gave us total size of the imaging area of 161×60 mm that allowed to capture all evolution of bag-breakup. The recording was performed at 3990 fps with exposure time of 1/50000 s. There were up to 700 frames (175 ms) in each record. The side view was used to obtain detailed data on the dynamics of the resulting structures: the shape of the structure before and during bag-breakup, the speed and size of the droplets formed.

Top view was only used to assess shape of bag-breakup in horizontal plane. It was done with the Optronis CamReco CR3000x2 high-speed camera. The camera was located at a distance of 112 cm from the surface (scale 102 μm/px). The recording was performed at 1250 fps with exposure time of 1/5000 s, the image size was 1696×720 px (173×74 mm). Since we used the same LED light source for side and top filming, only side view was made in shadowgraph setup.

4. Processing of high-speed images sequences

High-speed records of the bag-breakup process created using artificial disturbance (see figure 2) demonstrated that it developed though the same stages as bag-breakup at free water surface in laboratory conditions (compare with [1]). Analysis of high-speed records confirmed that there are two significantly different stages at which the spay in generated. First a rupture of the film takes place, which leads to the formation of small droplets, then the remaining after the rupture of the liquid film "rims" fragment into large drops.

Quantitative data on the characteristics and dynamics of droplets formed on both stages of bag-breakup fragmentation was obtained using specially developed software, that implements edge detection, segmentation, Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) methods. Image processing sequence consisted of two main steps: droplet detection and droplet tracking.

Position of all visible droplets on each frame of the record was detected using image processing sequence is shown in figure 3, for a fragment of one frame. We previously developed this method of
image segmentations for water surface detection in laser measurements, it is described in details in [10]. The method consist of several steps: background calculation and subtraction, edge detection with sobel of canny operator, morphological operations to remove noise and fill closed areas. The main feature of this sequence is logical ‘or’ performed with binary initial image at this step: this preserves small droplets keeping the noise low. At the last step positions, sizes and shapes of all isolated regions are calculated. Initial disturbance and "rim" are detected the similar way with different thresholds and neglected. The result of algorithm is position and size of every droplet on every frame of side view records (figure 4). Tuning of the parameters of the algorithm was made manually for each series of records. The algorithm can only detect droplets larger than 100 µm for images captured with this side view setup, but same algorithm can be used for smaller droplets using video with higher resolution.

Figure 2. Example of images obtained from the side camera (time points 83, 110, 113 and 120 ms) for wind speed $U_{10} = 21.8$ m/s. 1 – initial disturbance, 2 – rim, 3 – film, 4 – film rupture, 5 – film drops, 6 – rim drops. Full image width 161 mm.

Figure 3. Image processing sequence for a frame at 113 ms after film puncture, $U_{10} = 21.8$ m/s, 81 mm downwind the initial disturbance, 33 mm above surface. (a) – initial image, (b) – binary image with marked droplet areas, (c) – detected droplets (green circles – detected droplets, red – neglected parts of “rim”).
Straightforward particle tracking was not applicable for droplet tracking in present situation due to high visible density of particles at early moments after rapture. Velocities of droplets were roughly estimated by particle imaging velocimetry algorithm to simplify tracking problem. This was possible because most droplets in every particular area of image have similar velocities. We used custom PIV processing software that we developed for previous studies of air velocities in marine boundary layer [11]. Velocities were retrieved by splitting frames into small interrogation windows (128×128 px with 50% overlapping) in which overall displacement of particles was computed using cross-correlation. Only one iteration with tree-point interpolation for CCF maximum was used. Velocity fields were filtered using maximum and minimum velocity thresholds, 2-dimensional median filtering is space domain. PIV resulted in the velocity field on rectangular grid for every frame of the record (figure 5).

Custom tracking algorithm was developed in order to retrieve droplet trajectories. We run tracking backward in time as visible density of droplet decreases over time and it was easier to separate trajectories. Starting from the end of the record for every droplet on frame we tried to find appropriate droplet on previous frame in the vicinity of its assumed position. To define the search area position we used estimations of particle velocity and acceleration using two methods. PIV velocity field were interpolated to position of every droplet of the frame gave us estimate of velocity. Parabolic extrapolation for coordinated of four previously found points of current trajectory assuming a constant acceleration gave us velocity and acceleration. We used a combination of these data depending of its confidence: the first method is used for trajectories containing less than 4 known points, the average with weights (based on confidence) between two methods is used otherwise. Even if a drop has not been detected on one or two consecutive frames, the trajectory was constructed. The trajectory search stops when there are no droplets found in the vicinity of the expected position or the radius of the droplet found is more than 3 times different from the current one. If two trajectories find the same drop, the current drop position is assigned to the trajectory, the distance to the supposed point of which is smaller. The example of droplet tracking is shown on figure 6.

Postprocessing of trajectories consisted of filtering and combining split trajectories. Motionless trajectories with median displacement less than 0.001 px/frame and trajectories shorter than 10 frames are rejected as noise. The algorithm can lose the particle for several frames due to visible overlapping of the particles. To address this problem the standard deviation of the found positions and the polynomial extrapolation was calculated for each non-intersecting in time pair of trajectories. The trajectories were combined into one in case of low deviation. This combination is repeated until all split trajectories combined. This algorithm enables assigning more than 75% of droplets to trajectories for most part for the experimental condition and retrieving of more than 500 separate trajectories for some of the records. The example of retrieved trajectories is show on figure 7.

5. Conclusion

The dominant process of spray generation during wind-wave interaction – bag-breakup fragmentation can be investigated separately under controlled conditions by artificial creation of initial disturbance when separate bag-breakup event is forcefully generated in a dried high-speed wind-wave flume with water reservoir installed under the working section. Bag-breakup fragmentation from artificial disturbance developed through the same stages as bag-breakup on free water surface.

Characteristics of the generated spray can be obtained via high-speed shooting in shadowgraph configuration with special image processing sequence intended to identify the droplets on the images and track their trajectories based on the combination of PIV and reversed in time particle tracking. The data obtained by this method in combination with the statistics of the occurrence of "bags" can be used to construct the empirical function of spray generation.
Figure 4. Position of all droplets found on all frames in one record, color represents frame number, full image width 117 mm, $U_{10} = 21.8$ m/s

Figure 5. Approximate velocity field obtained by PIV interpolated to position of each droplet (shown in circles) for equivalent wind speed $U_{10} = 21.8$ m/s.

Figure 6. Example of a trajectory search for equivalent wind speed $U_{10} = 21.8$ m/s. Circles shows the search area near the assumed position. Blue lines are the previous 4 points of each trajectory. Red dots positions of all droplets on the frame.

Figure 7. All trajectories found in one record ($U_{10} = 21.8$ m/s); example frame is 6.2 ms after film puncture. Full image width 117 mm.

Acknowledgements
Carrying out experiments themselves was supported by Russian Science Foundation (Agreement No. 19-17-00209); designing of methods of measurements including: optical and visualization scheme, methods of measurements of the air flow and wave field parameters were supported by Russian Science Foundation (No 18-77-00074); the development of the software for video processing was supported by the Grant of the President no. MK-3184.2019.5 and RFBR project No. 19-05-00249.

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