Direct numerical simulation of bag-breakup - mechanism of sea spray generation in strong winds

A N Zotova, Yu I Troitskaya, D A Sergeev and A A Kandaurov
Institute of Applied Physics, Nizhny Novgorod, Russia
E-mail: aniazotova@yandex.ru

Abstract. For the direct numerical simulation of the bag-breakup phenomenon, the Gerris flow solver was used. As an initial configuration for numerical simulation a drop of liquid was placed in the air flow. A drop of water with a diameter of 1 cm (the characteristic size of the perturbation from which the bag arises) placed in the air stream at a speed of 20 m/s corresponds best to the experimental situation, such a system is characterized by the Weber number $W_e = 54$. Modeling the dynamics of two media with very different densities, such as water and air, require a lot of computational time, so we used liquids that differ in density by a factor of 10, but to keep the same Weber number, we changed the other parameters of the problem. The calculation was carried out with keeping the same Reynolds number and also with the Reynolds number reduced and increased by a factor of 10. In our simulation just as in an experiment under the action of an air stream a drop is blown into a micro-sail that bursts to form a micro-spray. As the Reynolds number decreases (with increasing of viscosity of both media), the process of destruction of the drop after the formation of a micro-sail from it changes.

1. Introduction
The flow of apparent and latent heat between the atmosphere and the ocean play an important role in the development of storms and tropical hurricanes [1]. A major contribution to heat transfer at the boundary between the atmosphere and the ocean is caused by sea splashes - water droplets ranging in size from $10 \text{nm}$ to several millimeters, injected from the sea surface as a result of waves breaking in the coastal zone or during strong winds. At the moment, there are several basic mechanisms of spray generation over the sea surface: fragmentation of liquid “fingers”, rupture of underwater bubbles, and, as was shown in recent works [2], bag-breakup mechanism. In [2] the mechanisms of spray generation under hurricane winds were experimentally studied and it was found that for friction velocity $u^* > 1 \text{ m/s}$ (for wind speeds at 10 m height exceeding 20 m/s), bag-breakup determines the contribution to the formation of large droplets.

A typical event of this type begins with a small-scale increase in the water surface, which then turns into a “micro-sail”, swells into a water film bounded by a thicker rim, and finally explodes, producing hundreds of droplets. The mean values of the radii $R$ and the lifetimes $\tau$ of bags estimated as $\langle R \rangle \sim 10^{-2} \text{ m}$ and $\langle \tau \rangle \sim 10^{-2} \text{ s}$, as a rule, decrease with increasing wind speed [2]. In the dynamics of engineering fluids [2], this phenomenon is known as the “bag-breakup” mode of liquid fragmentation in gas streams.

Experimental study of the phenomenon of bag-breakup in full-scale conditions is extremely difficult, but under laboratory conditions such studies are conducted. A separate bag-breakup
The event was investigated in a high-speed wind-wave channel with a small reservoir set at a distance of 7.5 m from its beginning. The initial perturbation, from which the bag develops, was artificially created in a given place using a jet from a submerged nozzle. The surface of the water around the experimental area was covered with a damping material. Simultaneous multi-stream high-speed shooting was used. Several frames of one of the received video recordings are shown in Figure 1.

![Figure 1. Forming and breaking of the bag (side view).](image)

The processing of the data obtained is laborious and time-consuming. In this situation it is also useful to carry out a numerical experiment that will allow us to study in more detail the processes leading to droplets in the investigated regime, and also to study the influence of various external factors on these processes.

2. The Gerris flow solver

For the direct numerical simulation of the bag-breakup phenomenon, the Gerris flow solver was used [3, 4]. Gerris is a software package for solving incompressible Euler and Navier-Stokes equations, combining the quad/octree adaptive mesh refinement method, projection method and multi-level Poisson solver. Complex solid boundaries are processed by the cartesian VOF method.

In Gerris, a numerical algorithm is implemented that solves the Navier-Stokes equations for incompressible media with variable density and surface tension:

\[ \rho \left( \partial_t \vec{u} + \vec{u} \nabla \rho \right) = -\nabla p + \nabla \left( 2\mu \vec{D} \right) + \sigma \kappa \delta_s \vec{n} \]

\[ \partial_t \rho + \nabla \left( \rho \vec{u} \right) = 0 \]

\[ \nabla \vec{u} = 0 \]

where \( \vec{u} = (u, v, w) \) - the fluid velocity, \( \rho \) - the density of the liquid, \( \mu \) - the dynamic viscosity, and \( \vec{D} \) - the deformation tensor defined as \( D_{ij} \equiv \left( \partial_i u_j + \partial_j u_i \right) / 2 \). The Dirac distribution function \( \delta_s \) expresses the fact that the surface tension term is concentrated at the media interface; \( \sigma \) - the surface tension, \( \kappa \) and \( \vec{n} \) - the curvature and the normal to the interface.

For two-phase flows, the volume fraction \( c \) of the first liquid is introduced and the density and viscosity are determined as

\[ \rho \equiv c \rho_1 + (1 - c) \rho_2 \]

\[ \mu \equiv c \mu_1 + (1 - c) \mu_2 \]

where \( \rho_1, \rho_2 \) and \( \mu_1, \mu_2 \) are the densities and viscosities of the first and second media, respectively.

Then the advection equation for density can be replaced by the equivalent advection equation for the volume fraction of the liquid:

\[ \partial_t c + \nabla \left( c \vec{u} \right) = 0 \]
To solve the advection equation for the volume fraction, the piecewise linear geometric VOF method [5] is used, which is generalized for quad/octree spatial discretization.

3. Simulation

We decided to start the simulation not with a geometrically complex configuration of the initial perturbation, from which the bag was developed in the experiment [2], but with the problem of a simpler geometry: a drop of liquid was placed in the air flow (see Figure 2). The droplet dynamics under different conditions was studied experimentally, theoretically and numerically, and it was shown [6] that the droplet destruction mechanism depends on the Weber number characterizing the system $\text{We} = \frac{\rho_a v^2 D}{\sigma}$, where $\rho_a$ – the density of the external medium, $v$ – the velocity of the external medium, $D$ – the initial diameter of the drop, $\sigma$ – the surface tension.

![Figure 2. Configuration of the problem.](image)

A drop of water with a diameter of 1 cm (the characteristic size of the perturbation from which the bag arises) placed in the air stream at a speed of 20 m/s corresponds best to the experimental situation, such a system is characterized by the Weber number $\text{We} = 54$ and the Reynolds number $\text{Re} = 1.1 \cdot 10^4$.

![Figure 3. The result of numerical simulation of the formation and rupture of the bag with corresponding to the initial problem numbers $\text{We}$ and $\text{Oh}_d$, $\text{Re}$ increased by 10 times ($\rho'_a = \rho_a \cdot 100; v' = v/10; \mu'_a = \mu_a; \mu'_d = \mu_d; \sigma' = \sigma$).](image)

Modeling the dynamics of two media with very different densities, such as water and air, require a lot of computational time, so we used liquids that differ in density by a factor of 10 (air density $\rho_a$ was increased 100 times), but to keep the Weber number fixed in one case we changed the value of velocity of the external medium ($v' = v/10$).
Figure 4. The result of numerical simulation of the formation and rupture of the bag with corresponding to the initial problem numbers $We$ and $Re$ ($\rho'_a = \rho_a \cdot 100; v' = v/10; \mu'_a = \mu_a \cdot 10; \mu'_d = \mu_d \cdot 10; \sigma' = \sigma$).

Figure 5. The result of numerical simulation of the formation and rupture of the bag with corresponding to the initial problem number $We$ and the number $Re$ reduced by a factor of 10 ($\rho'_a = \rho_a \cdot 100; v' = v/10; \mu'_a = \mu_a \cdot 10; \mu'_d = \mu_d \cdot 10; \sigma' = \sigma$).

The calculation was carried out with keeping the Reynolds number $Re = \frac{\rho_a D v}{\mu_a}$ fixed, see Fig. 4 ($\mu'_a = \mu_a \cdot 10; \mu'_d = \mu_d \cdot 10$), and with the Reynolds number 10 times increased, see Fig. 3 ($\mu'_a = \mu_a; \mu'_d = \mu_d$), and 10 times reduced, see Fig. 5 ($\mu'_a = \mu_a \cdot 100; \mu'_d = \mu_d \cdot 100$), compared to the Reynolds number for the experimental configuration. The Ohnesorge number $Oh_d = \frac{\mu_d}{(\rho_d D \sigma)^{1/2}}$, which determines the Weber numbers, for which there are transitions from one droplet destruction regime to another, for all this cases is $\leq 0.1$, so the effect of drop viscosity is not significant [7].

Also in our calculations, keeping the Weber and Reynolds numbers fixed was provided by another set of parameters: $\rho'_a = \rho_a \cdot 100; v' = v; \mu'_a = \mu_a \cdot 100; \mu'_d = \mu_d \cdot 100; \sigma' = \sigma \cdot 100$ (see Fig. 6).

The simulation results are shown in Figures 3 - 6. It can be seen that, just as in the experiment, under the action of the air flow the drop inflates into a micro-sail, which bursts with the formation of micro-spray. The process of destruction of the drop after the formation of a micro-sail from it changes: for Reynolds numbers $Re = 1.1 \cdot 10^5$ and $Re = 1.1 \cdot 10^4$ after the formation of a break and small splashes in the center of the sail, a rim is formed along the
Figure 6. The result of numerical simulation of the formation and rupture of the bag with corresponding to the initial problem numbers $We$ and $Re$ ($\rho'_a = \rho_a \cdot 100; v' = v; \mu'_a = \mu_a \cdot 100; \mu'_d = \mu_d \cdot 100; \sigma' = \sigma \cdot 100$).

edge of the break, which is subsequently separated from the rest of the sail; for the Reynolds number $Re = 1.1 \cdot 10^3$ after the formation of a break in the center of the sail, the edge of the break continues to move to the edge of the micro-sail.

Also, calculations have shown that the mechanism of droplet destruction does not change when the parameters of the problem change in such a way that the Weber and Reynolds numbers remain unchanged.

Acknowledgments
Carrying out experiments themselves was supported by Russian Science Foundation (Agreement No. 14-17-00667); 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 Foundation of Basic Research (No 18-55-50005, 18-05-60299, 18-35-00658, 18-35-20068); the development of the software for video processing was supported by the Grant of the President no. MK-2041.2017.5.

References
[1] Andreas E L and Emanuel K A 2001 *J. Atmos. Sci.* **58** 3741–3751
[2] Troitskaya Yu, Kandaurov A, Ermakova O, Kozlov D, Sergeev D and Zilitinkevich S 2017 *Sci. Rep.* **7** 1614
[3] Popinet S 2003 *J. Comput. Phys.* **190** 572–600
[4] Popinet S 2009 *J. Comput. Phys.* **228** 5838–5866
[5] Scardovelli R and Zaleski S 1999 *Annual Review of Fluid Mechanics* **31** (1) 567–603
[6] Pilch M and Erdman C A 1987 *Int. J. Multiphase Flow* **13** (6) 741–757
[7] Krzeczkowski S A 1980 *Int. J. Multiphase Flow* **6** 227–239