Bag-breakup – mechanism of sea spray generation in strong winds

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Sea spray

• typical phenomenon for the boundary layer of the atmosphere with a strong wind

• plays an important role in the transfer of heat and momentum

• It is difficult to estimate the number and size of droplets in a sea spray, because the mechanisms of its occurrence are poorly understood
Investigation of the spray generation mechanisms at high winds

The purposes:

• To investigate mechanisms responsible for spray generation at strong wind, classify them and quantify the efficiency of the disclosed mechanisms

• To construct the spray generation function at strong winds basing on disclosed mechanisms of their generation

• To estimate momentum and heat fluxes at storm winds taking into account the effect of spray
Experimental setup

The high-speed wind-wave flume of IAP, Nizhny Novgorod, Russia

- Dimensions of the channel
  10m x 0.4m x 0.4 m
- The air-flow velocity corresponds to 10-m neutral wind speed $U_{10}$ from 4 to 40 m/s

Annular wind-wave channel Aeolotron at the University of Heidelberg, Germany

- 60 cm width
- 2.4 m height
- Circumference of 27.3 m at the inner wall
- Water depth during experiments 1.0 m
- Water volume 18.0 m$^3$
- Air space volume 24 m$^3$
The main method: high speed photography through the transparent walls and upper lid of the channel

Experimental setup for the shadow method

MEMRECAM HX-3 High Speed Camera System

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MEMRECAM HX-3 High Speed Mode

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Complex structure of a wind – wave crest $U_{10}=29 \text{ m/s}$

2500 fps, Nikkor35 f1.4, Distance = 100-140 cm

Investigation of details enabled us to specify 3 types of the spray generating phenomena.
Spray generation mechanisms

**Fragmentation of liquid ligaments (top view)**

- Wind speed
  \[ U_{10} = 25.9 \text{ m/s} \]
- Camera details:
  - f = 85 mm
  - Samyang 85 mm f/1.4
  - Distance = 65 cm
  - Scale = 73 µm/px
  - 10000 fps

**Bursting of the underwater bubble (side view)**

- Wind speed
  \[ U_{10} = 27.8 \text{ m/s} \]
- Camera details:
  - f = 55 mm
  - Samyang 85 mm f/1.4
  - Distance = 65 cm
  - Scale = 73 µm/px
  - 2000 fps

**Bag breakup (side view)**

- Wind speed
  \[ U_{10} = 27.8 \text{ m/s} \]
- Camera details:
  - f = 55 mm
  - Samyang 85 mm f/1.4
  - Distance = 65 cm
  - Scale = 73 µm/px
  - 2000 fps
Spray generation at the wave crests ("bag breakup")

LASIF, Luminy, 250 fps, courtesy by H. Branger, 1990, 14 m/s

Wind speed $U_{10} = 27.7$ m/s  Width 74 mm

Aeolotron: The Heidelberg wind/wave facility
“Bag breakup”

Bag-breakup mode of fragmentation of a droplet


Bag-breakup of liquid jets in crossflow

The specific number of spray generating events (per unit time per unit area) versus friction velocity

The number of the bag-breakup events dominates at high winds

"Bag-breakup" SGF
The size spectra of droplets produced by a sole bag

"Bags" generate spray in two ways

1. Rupturing the canopy of inflated bag
2. Fragmentation of the rim

\[ F_{drops}(r,R) = F_{film}(r,R) + F_{rim}(r,R) \]
Rupturing the canopy of inflated bag (similarly to bursting of an underwater bubble)

Fragmentation of the bag rim (similarly to the fragmentation of the rim at of a droplet in gaseous flow)

H. Lhuissier and E. Villermaux Bursting bubble aerosols J. Fluid Mech., V. 696, 2012, p. 5-44


Bag breakup SGF in the lab for $u^*$ from 1 m/s to 2 m/s with an increment 0.2 m/s

The experimental setup for studying the mechanism of the spray production due to the bag-breakup fragmentation with the use of the artificial disturbance.

Video from side-view camera for $u_*=0.61 \text{ m/s}$.
The canopy droplet production

Plateau–Rayleigh versus Rayleigh-Taylor instability


\[ \tau_{R-T} \sim \left( \frac{\sigma}{\rho_w \gamma^3} \right)^{1/4} \]
\[ \gamma = \frac{V^2}{R} \]
\[ V = \sqrt{\frac{2\sigma}{\rho_w h}} \]

Right: Plateau–Rayleigh instability

\[ \tau_{P-R} \sim \left( \frac{\rho_w \delta^3}{\sigma} \right)^{1/2} \]
\[ \delta \sim h \]

The P-R instability is faster than R-T one

\[ \frac{\tau_{P-R}}{\tau_{R-T}} \sim \left( \frac{h}{R} \right)^{3/4} \ll 1 \]
The rim droplet production

Droplet formation during fragmentation of the rim

Type 1 droplets
Small number of the large droplets formed as the result of development of the instability at the rear edge of the bag before the rupture of the canopy.

Type 2 droplets
Smaller droplets formed due to the capillary (P-R) instability of the remaining rim.
The size spectra of the droplets from one bag of a certain radius $R=20$ mm at different values of the wind friction velocity $u_*$
Open questions

• What is the mechanism for the formation of the perturbation from which bag evolves?

• What factors influence its size?

• How does the size of the disturbance and the wind speed affect the size of the canopy and the thickness of its film?

• What are the parameters of the bag and how do they affect the size of the droplets resulting from its rupture?

and so on ...
Configuration of the problem

\[ \rho_w = 1000. \text{ kg/m}^3 \]
\[ \rho_a = 100. \text{ kg/m}^3 \]
\[ \mu_w = 1.003 \times 10^{-3} \text{ Pa}\cdot\text{s} \]
\[ \mu_a = 1.8 \times 10^{-5} \text{ Pa}\cdot\text{s} \]
\[ \sigma = 72.9 \times 10^{-3} \text{ N/m} \]

\[ \vec{v} = 20 \text{ m/s} \]

\[ D = 1 \text{ cm} \]

\[ We = \frac{\rho_a \vec{v}^2 D}{\sigma} \]
\[ Re = \frac{\rho_a D \vec{v}}{\mu_a} \]
\[ Oh_w = \frac{\mu_w}{(\rho_w D \sigma)^{1/2}} \]

\[ We = 55 \]
\[ Re = 11 \times 10^3 \]
\[ Oh_w = 10^{-3} \]
Parameters of the problem

the lower $\rho_a / \rho_w$

the lower computational cost

$\rho^* = \frac{\rho_a}{\rho_w} = 1000$  $\rightarrow$  $\rho'_a = \rho_a \cdot 100$  $\rightarrow$  $\rho^* = \frac{\rho'_a}{\rho'_w} = 10$

The droplet destruction mechanism depends on the Weber number characterizing the system, so to keep the same Weber number we changed the value of the external medium velocity. In order to reduce the required resolution we changed the value of dynamic viscosity.

$We = const$

$Re = Re \cdot 10$

$\begin{align*}
\rho'_a &= \rho_a \cdot 100 \\
\nu' &= \nu / 10 \\
\mu'_a &= \mu_a \cdot 100
\end{align*}$
Results of direct numerical simulation in Gerris

We corresponds to the initial problem numbers, Re reduced by a factor of 10 ($\rho_a' = \rho_a \cdot 100; \nu' = \nu/10; \mu_a' = \mu_a \cdot 100; \mu_w' = \mu_w \cdot 100; \sigma' = \sigma$).
Results of direct numerical simulation in Basilisk

The same parameters and initial conditions as in Gerris, but…

Level:
Initial – 6
Adaptive - 8

color represents $u_x$

Result is similar for $u_x = u_x/2$ ($We = We/4$)
Results of direct numerical simulation in Basilisk

- **Level:**
  - Initial – 6
  - Adaptive - 8

- **Boundary Conditions:**
  - **inflow BC for** $u_x$
  - **free-slip BC**
  - **outflow BC**

- **Equation:**
  $u_x = 0$
Results of direct numerical simulation in Basilisk

```c
foreach()
if (f[0] > 0) {
    u.x[] = v_a;
} boundary ((scalar *){u});
```
Issues

• The results are not the same in Gerris and in Basilisk – no bag-breakup in Basilisk

• Test simulation slows down, when core number > 18

# Octree, 100 steps, **757.982 CPU**, 760.6 real, 5.29e+04 points.step/s, 34 var
# 8 procs, MPI: min 2e+02 (27%) avg 2.2e+02 (29%) max 2.3e+02 (30%)

# Octree, 100 steps, **729.01 CPU**, 731.6 real, 5.5e+04 points.step/s, 34 var
# 10 procs, MPI: min 1.9e+02 (26%) avg 2.1e+02 (29%) max 2.5e+02 (34%)

# Octree, 100 steps, **673.271 CPU**, 676.5 real, 5.95e+04 points.step/s, 34 var
# 18 procs, MPI: min 1.3e+02 (19%) avg 1.8e+02 (26%) max 2.1e+02 (31%)

# Octree, 100 steps, **791.857 CPU**, 796.3 real, 5.06e+04 points.step/s, 34 var
# 24 procs, MPI: min 1.2e+02 (15%) avg 1.6e+02 (21%) max 1.9e+02 (24%)

# Octree, 100 steps, **1356.3 CPU**, 1362 real, 2.96e+04 points.step/s, 34 var
# 36 procs, MPI: min 1.2e+02 (8.8%) avg 1.7e+02 (12%) max 2e+02 (15%)
3 2 GfsSimulation GfsBox GfsGEdge {} {
  Time { end = 10. }
  # Time { end = 0.1 }
  # ApproxProjectionParams { tolerance = 1e-6 }
  # ProjectionParams { tolerance = 1e-6 }

  EventBalance { istep = 1 } 0.1

  Refine 5

  Global {
    #define RHO_L 1000.
    #define RHO_G 100.
    #define MU_L 1.003e-3
    #define MU_G 1.8e-5
    #define VAR(T,min,max) (min + CLAMP(T,0,1)*(max - min))
    #define RHO(T) VAR(T, RHO_G/RHO_L, 1.)
    #define MUR(T) VAR(T, MU_G/MU_L, 1.)
  }

  VariableTracerVOF T
  VariableFiltered T1 T 1

  VariableCurvature K T Kmax
  SourceTension T 4.672*1e-4 K

  InitFraction T (x*x + y*y + z*z - 0.2*0.2) { tx = -0.2 }

  AdaptVorticity { istep = 1 } { maxlevel = 9 cmax = 1e-2 }
  AdaptFunction { istart = 5 istep = 10 } {
    cmax = 0.2
    maxlevel = 8
    cfactor = 2
  } (T > 0 && T < 1 ? dL*Kmax : 0)

  PhysicalParams { alpha = 1./RHO(T1) }
  SourceViscosity 100*16*1e-6*MUR(T1)

}
#include "grid/octree.h"
#include "navier-stokes/centered.h"
#include "vof.h"
#include "tension.h"
#include "view.h"
#include "two-phase.h"
#include "tag.h"

#define RHOR 10. /**< rho_a*100 */
#define MUR 55.6
#define sig (4.672*1e-4) /**< dimensionless */
#define vis_w (16.*1e-6) /**< dimensionless */
#define rad 0.2
#define v_a 0.8 /**< u/10 */
#define cx (-0.2)
#define cy 0.
#define cz 0.
#define vis_w_new (vis_w*100.) /**< mu_a*100, mu_w*100 */

int adaptmax;

int main() {
  L0 = 3.;
  origin (-0.5, -L0/2., -L0/2.);
  f.sigma = sig;
  TOLERANCE = 1e-6;
  rho1 = 1.;
  rho2 = 1./RHOR;
  mu1 = vis_w_new;
  mu2 = vis_w_new/MUR;
  init_grid (64);
  adaptmax = 8;
  run(); }

event init (t = 0) {
  if (!restore (file = "restart")) {
    refine (level < adaptmax &&
            sq(0.9*rad) - sq(x-cx) - sq(y-cy) - sq(z-cz) < 0.0 &&
            sq(1.1*rad) - sq(x-cx) - sq(y-cy) - sq(z-cz) > 0.0);
    fraction (f, - (sq(x-cx) + sq(y-cy) + sq(z-cz) - sq(rad)));
  }

  /** initial velocity */
  foreach()
    if (f[] > 0) {
      u.x[] = v_a; }
  boundary ((scalar *){u});

  event adapt (i++) {
    double uemax = 1e-2;
    adapt_wavelet (f,u), (double[]){0.01,uemax,uemax,uemax}, adaptmax, 6);}

  /** At the walls there are outflow */
  u.n[top] = neumann(0.);
  p[top] = dirichlet(0.);
  pf[top] = dirichlet(0.);
  u.n[bottom] = neumann(0.);
  p[bottom] = dirichlet(0.);
  pf[bottom] = dirichlet(0.);
  u.n[front] = neumann(0.);
  p[front] = dirichlet(0.);
  pf[front] = dirichlet(0.);
  u.n[back] = neumann(0.);
  p[back] = dirichlet(0.);
  pf[back] = dirichlet(0.);

  /** The walls are free-slip */
  //**u.n[top] = neumann(0.);
  u.t[top] = neumann(0.);
  u.n[bottom] = neumann(0.);
  u.t[bottom] = neumann(0.);
  u.n[front] = neumann(0.);
  u.t[front] = neumann(0.);
  u.n[back] = neumann(0.);
  u.t[back] = neumann(0.);*/