Breakup of finite size colloidal aggregates in turbulent flow

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Breakup of aggregates
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- Processing of industrial colloids, flocculation in (waste)water treatment

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- Processing of industrial colloids, flocculation in (waste)water treatment
- Evolution and transport of sediments and marine snow in natural waters

*Picture: Satellite image River Plate Estuary, 2010-03-10 ([www.eosnap.com](http://www.eosnap.com), 2014-03-12)*
Aggregate breakup in turbulence

Mechanism of breakup

Dynamics of breakup
Experimental setup

- Stationary turbulence, monitored by 3D PTV

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- Stationary turbulence, monitored by 3D PTV
- Inject a single pre-formed aggregate
- Follow the aggregate until (and beyond) breakup
- Determine local flow conditions that prevail at breakup

**Experimental setup**

**Aggregates**
- Made out of polystyrene colloids, $d_p = 420 \text{ nm}$
- Grown *in-situ* in the feed pipe, under oscillatory flow
- $d_{agg} = 1.4 \pm 0.4 \text{ mm}$
  Fractal dimension $d_f \sim 2.2$

**Flow device**
- $R_\lambda \approx 117$
- $\langle \varepsilon \rangle \approx 19 \text{ cm}^2/\text{s}^3$
- $\eta \approx 0.15 \text{ mm}$

Breakup experiments

Example of a breakup experiment

- $R_\lambda \approx 117$
- $\langle \varepsilon \rangle \approx 19 \text{ cm}^2/\text{s}^3$
- $\eta \approx 0.15 \text{ mm}$
- $d_{\text{agg}} \approx 1.4 \text{ mm}$
Example of a breakup experiment

- \( R_\lambda \approx 117 \)
- \( \langle \varepsilon \rangle \approx 19 \text{ cm}^2/\text{s}^3 \)
- \( \eta \approx 0.15 \text{ mm} \)
Hydrodynamic stress

Aggregate motion

- \( \frac{d_{agg}}{\eta} \approx 9 \pm 3 \)

- Aggregate Stokes number

\[
S_t = \frac{1}{18} \frac{\rho_{agg}}{\rho_f} \left(\frac{d_{agg}}{\eta}\right)^{3/4}
\]

\[= 0.3 \pm 0.1\]

⇒ Aggregate motion is influenced by inertia
Hydrodynamic stress

**Aggregate motion**

- \( \frac{d_{agg}}{\eta} \approx 9 \pm 3 \)

- Aggregate Stokes number
  \[
  St = \frac{1}{18} \frac{\rho_{agg}}{\rho_f} \left( \frac{d_{agg}}{\eta} \right)^{3/4}
  = 0.3 \pm 0.1
  \]

\( \Rightarrow \) Aggregate motion is influenced by inertia

Filter size to estimate \( u \)
Breakup mechanism: limiting cases

**Soft aggregates** (slow breakup)

- Bond breakup due to thermal motion of the colloids [1].

  - Depends on the duration the aggregate is subject to hydrodynamic stress.
  - *If true:* weak aggregates (=large aggregates) break earlier than stronger ones.

**Brittle aggregates** (fast breakup)

- Breakup caused by an abrupt breakup of bonds [2].

  - Occurs when the hydrodynamic stress exceeds a critical threshold.
  - *If true:* the hydrodynamic stress at breakup correlates with the aggregate size.

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Experimental results

Time lag from release to breakup

Shear stress at breakup

Drag stress at breakup

Weak

Strong

Aggregate strength

Weak

Aggregate strength

Weak

Aggregate strength

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Experimental results

Accumulation of shear stress

\[ \bar{\sigma}_{\text{shear}} \times \tau_\eta / \mu \]

Accumulation of drag stress

\[ \bar{\sigma}_{\text{drag}} \times \tau_\eta / \mu \]

\[ \bar{\sigma}_i = \frac{1}{\Delta t} \int_{t_b-\Delta t}^{t_b} \sigma_i \, dt \quad \Delta t \sim \tau_\eta \]

\[ R^2 = 0.022 \]

\[ R^2 = 0.21 \]
Breakup mechanism

3D PTV with large aggregates

- Hydrodynamic stress dominated by drag
- Breakup is caused by weak accumulation of stress

Sub-Kolmogorov aggregates

- Breakup mechanism

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Drag originates from the finite aggregate size

Sub-Kolmogorov aggregates

- Stress on small aggregates (in liquid) dominated by shear
Breakup mechanism

3D PTV with large aggregates

- Hydrodynamic stress dominated by drag
- Breakup is caused by weak accumulation of stress

Sub-Kolmogorov aggregates

- Drag originates from the finite aggregate size
- Stress on small aggregates (in liquid) dominated by shear
- Bonds within the aggregate store elastic energy
- Small aggregates exhibit faster response
Aggregate breakup in turbulence

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Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
  - Move as if they were heavy point particles

- Aggregates are small and heavy

\[ R < \eta \]
\[ \rho_a \gg \rho_f \]

\[
\begin{cases}
    \dot{v} = \frac{u - v}{\tau_s} \\
    \dot{x} = v
\end{cases}
\]

\[
\tau_s = \frac{(2\rho_a + \rho_f)R^2}{9\rho_f \nu}
\]

\[
St = \frac{\tau_s}{\tau_\eta}
\]
Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
  - Aggregates are small and heavy
    - Move as if they were heavy point particles
    - Subject to shear and drag stress

\[ R < \eta \]
\[ \rho_a \gg \rho_f \]

Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
  - Move as if they were heavy point particles
  - Subject to shear and drag stress
- Aggregates are small and heavy
- Predefined rule for breakup

\[ \sigma > \sigma_{cr} \]

\[ \frac{\tau_s}{\tau_\eta} = R < \eta \]

\[ \rho_a \gg \rho_f \]

\[ \sigma = \sqrt{\frac{2}{15}} \mu \left( \frac{\varepsilon}{\nu} \right)^{1/2} + \frac{3}{2} \mu \frac{|v - u|}{R} \]

Babler, Biferale, Lanotte (2012)
Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
  - Aggregates are small and heavy
    - Move as if they were heavy point particles
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- Predefined rule for breakup

Babler, Biferale, Lanotte (2012)
Numerical experiments

- Turbulent trajectories for heavy point particles in HIT are available on [http://turbase.cineca.it](http://turbase.cineca.it) (as part of EuHIT program)
  - Resolution $2048^3$
  - $Re_\lambda = 400$

$$f_{\sigma_{cr}} = \frac{1}{\langle \tau_{\sigma_{cr}} \rangle}$$

Babler, Biferale, Lanotte (2012)
Aerosols aggregates in HIT

- Aggregates of size $R/\eta = 0.1$ and varying density

![Graph showing the relationship between $f_{cr} \tau_\eta$ and $\sigma_{cr}/\sigma_0$.]

$\rho_a \sim \rho_f$
Aerosols aggregates in HIT

- Aggregates of size $R/\eta = 0.1$ and varying density

Tracers

$\rho_a \sim \rho_f$

$St=0.16$

$St=40$

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Aerosols aggregates in HIT

- Aggregates of size $R/\eta = 0.1$ and varying density

![Image of aggregates]

![Graph showing aggregates behavior]

Tracers $\rho_a \sim \rho_f$
Aerosols aggregates in HIT

- Aggregates of size $R/\eta = 0.1$ and varying density
- 3D-PTV Experiments $R/\eta = 18$, $St \approx 0.3$
Conclusions

We studied the breakup of finite size aggregates made out of fully destabilized polystyrene colloids in homogeneous isotropic turbulence by means of 3D-PTV.

Major findings are:

- Hydrodynamic stress is dominated by drag.
- Breakup is caused by weak accumulation of stress.

Both these findings are an effect of the large aggregate size.

Conclusions

Numerical simulations of small and brittle aggregates show that the breakup rate as a function of aggregate strength exhibits power law behavior for weak aggregates, followed by a sharp cut-off as the aggregate strength increases.

- Power law is controlled by the smooth part of the flow whose statistics are close to Gaussian.
- The sharp cut-off is caused by rare intermittent turbulent events.
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Drag originates from the finite aggregate size

- Stress on small aggregates (in liquid) dominated by shear
- Small aggregates exhibit faster response

Finite stress propagation inside the aggregate
Aim: Investigating the mechanism of breakup in turbulence by monitoring individual breakup events in well controlled experiments
Aim of this work

**Previous work:** Dynamics of breakup

**This work:** Mechanism of breakup
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