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A breakup of a droplet falling into a miscible solution

Michiko Shimokawa and Hidetsugu Sakaguchi

References

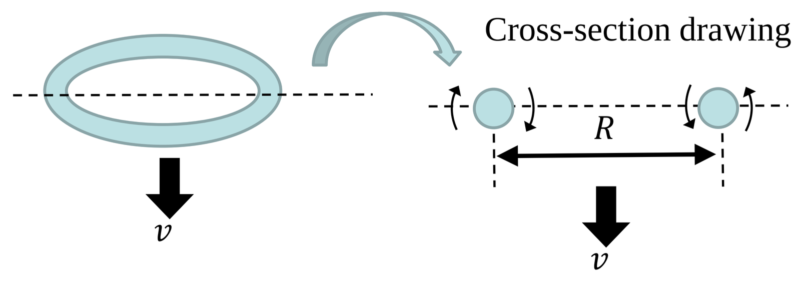
[1] Michiko Shimokawa *et al*., Phys. Rev. E **93**, 062214, 2016.

[2] Michiko Shimokawa and Hidetsugu Sakaguchi. Phys. Rev. Fluids **4**, 013603, 2019.

Introduction

● Vortex in our life: Bubble ring, vortex of cigarette, etc…

http://blogs.yahoo.co.jp/ssm_121/63201340.html



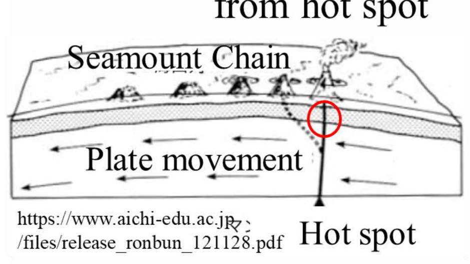
Vortex radius $R(t)$

$$R(t)^2 - R(0)^2 = \frac{gV\Delta\rho}{\pi\rho\Gamma} t$$

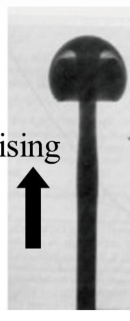
Γ: circulation
V: vortex volume
$\Delta\rho$: density difference

● Simple experiments to mimic nature provide to understand the nature.

・Magma rises from hot spot

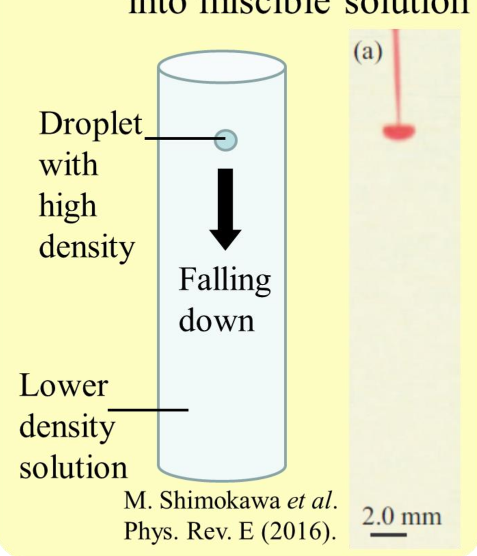


https://www.aichi-edu.ac.jp/.../files/release_ronbun_121128.pdf

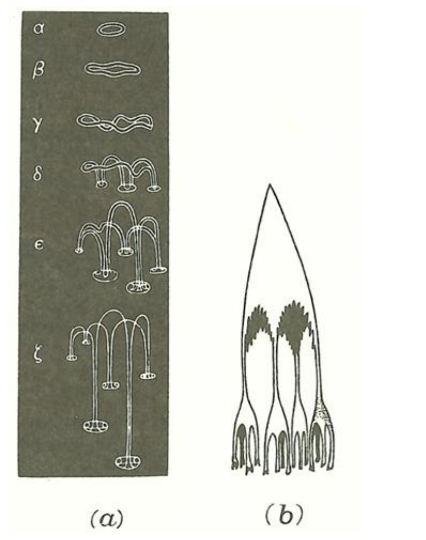


A.P Koppers *et al.* Nature Geoscience (2012).

・falling droplet into miscible solution



M. Shimokawa *et al.* Phys. Rev. E (2016).



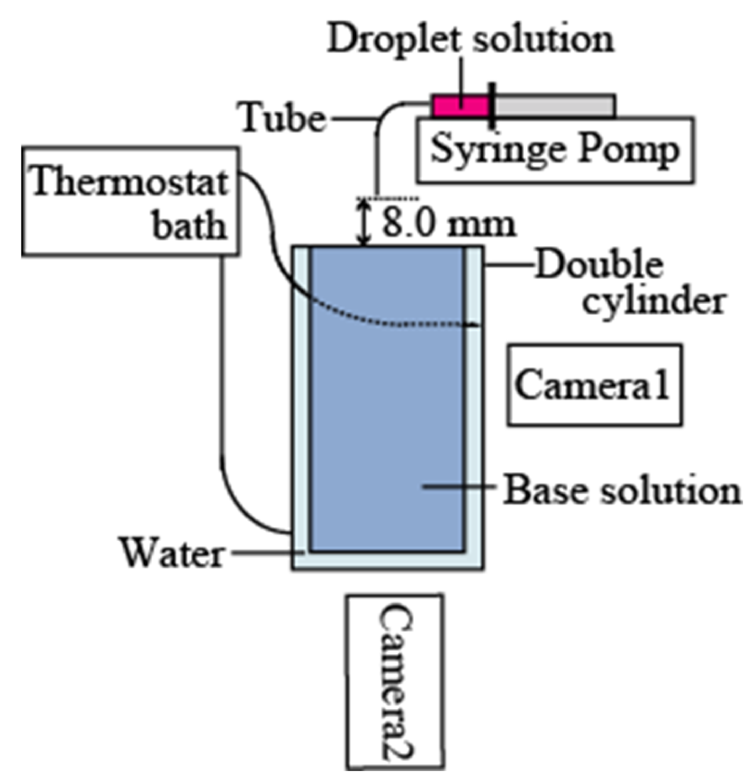
Falling drops. (a) ink in water, after J. J. Thomson and H. F. Newall; (b) fusel oil in paraffin, after Tomlinson.

D'arcy Thompson, "*On growth and form*" (1961).

Experimental Method

(1) A droplet is put on the surface of the base solution in the double cylinder.
(2) The process of the droplet is captured from lateral and bottom sides of the cylinder using cameras.

Droplet: Fe(SO4)aq+PEG
Base solution: Glycerine+PEG

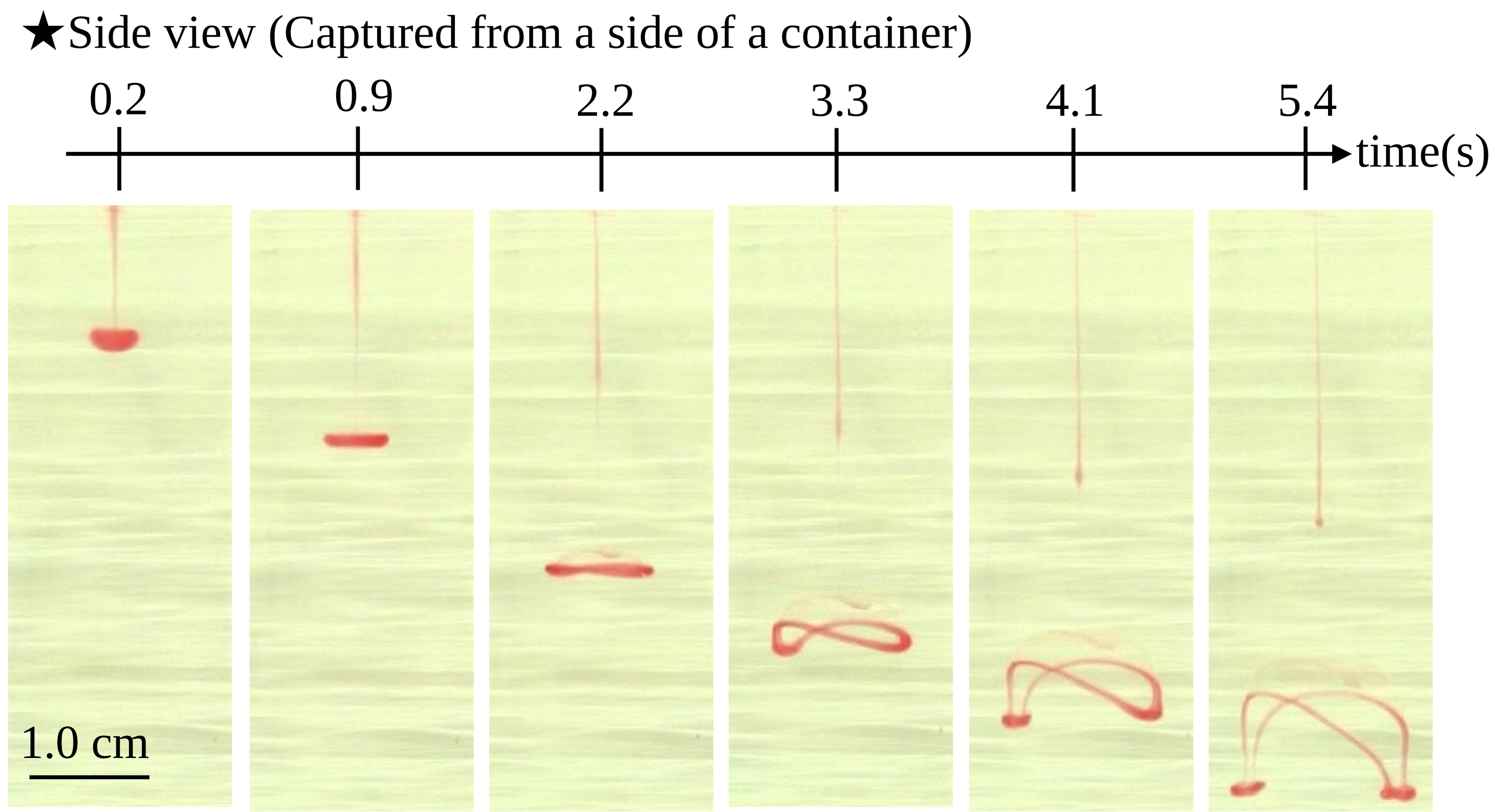


- r: A size of droplet is controlled by using a syringe pomp.
- μ: Viscosities of solutions are controlled by amount of PEG in the solutions. (The value of the droplet viscosity keeps a similar value to that of base solution in our experiments.)
- $\Delta\rho$: Density differences between two solutions are controlled by amount of Fe(SO4)aq in the droplet solution.
- The breakup process is captured from lateral side and bottom of a cylinder.
- Temperature is controlled by thermostat bath for keeping a viscosity constantly.

Experimental Results

● Time series of breakup and deformation of droplet
(droplet size r =1.3 mm, mode m = 2)

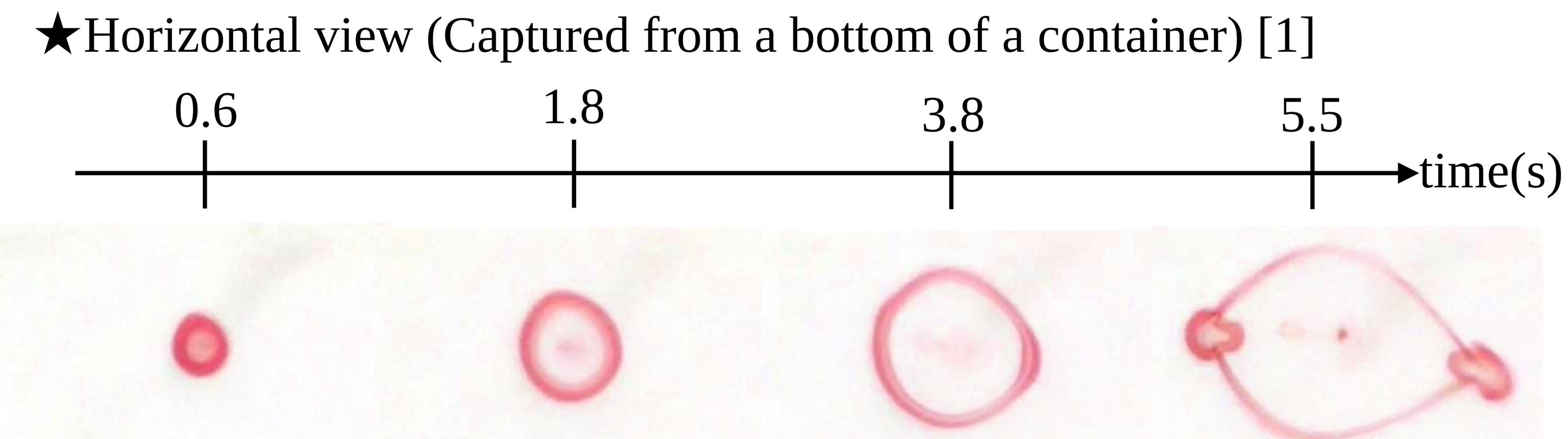
★Side view (Captured from a side of a container)



Vortex size increases

Vertical disturbance becomes large.

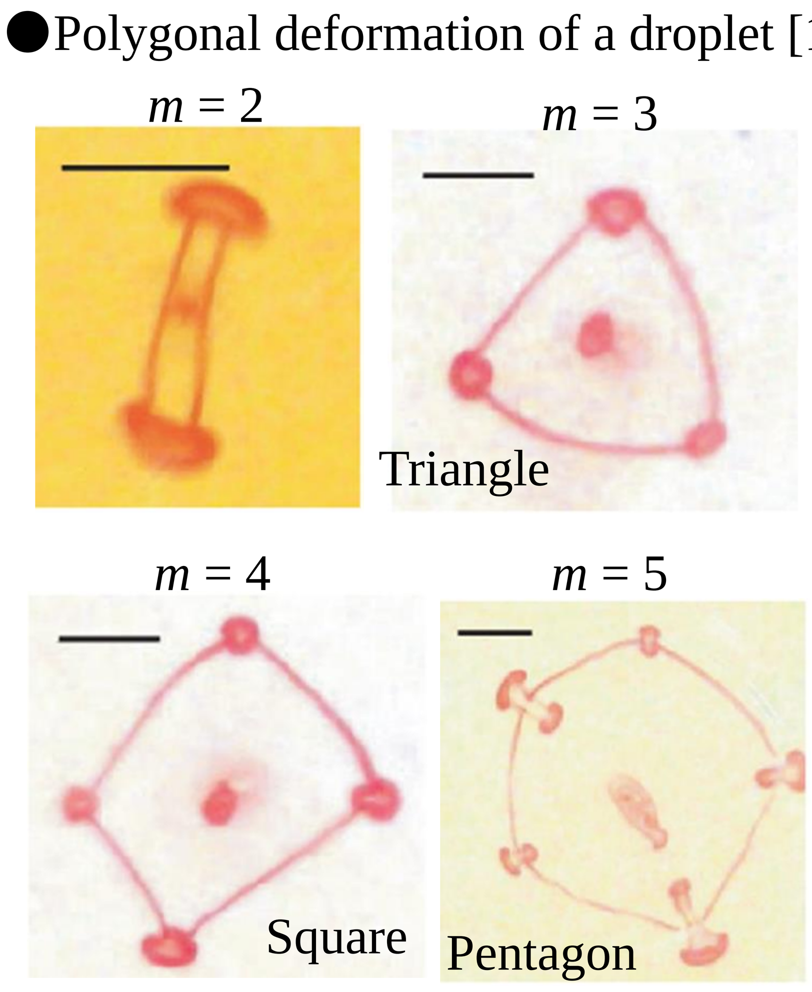
★Horizontal view (Captured from a bottom of a container) [1]



Vortex size increases

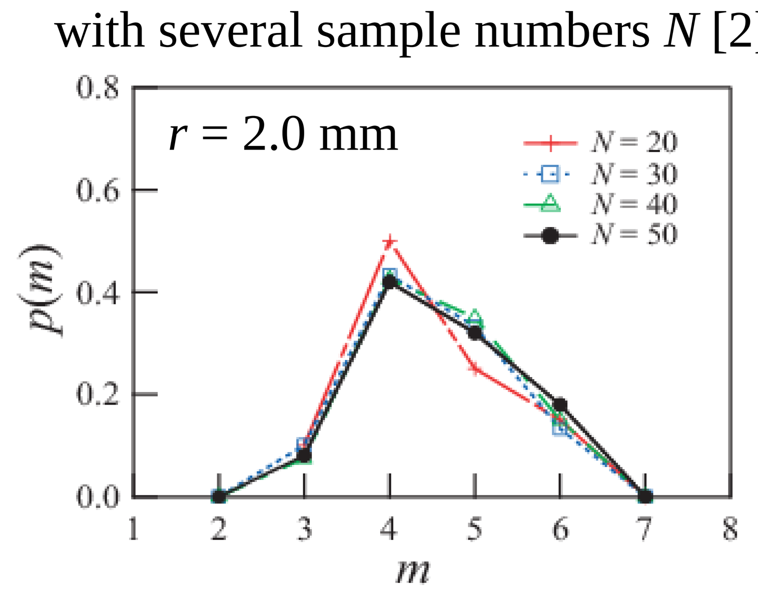
Disturbance becomes large.

● Polygonal deformation of a droplet [1]



A droplet deforms a polygonal shape.
(This is not reported in previous studies.)

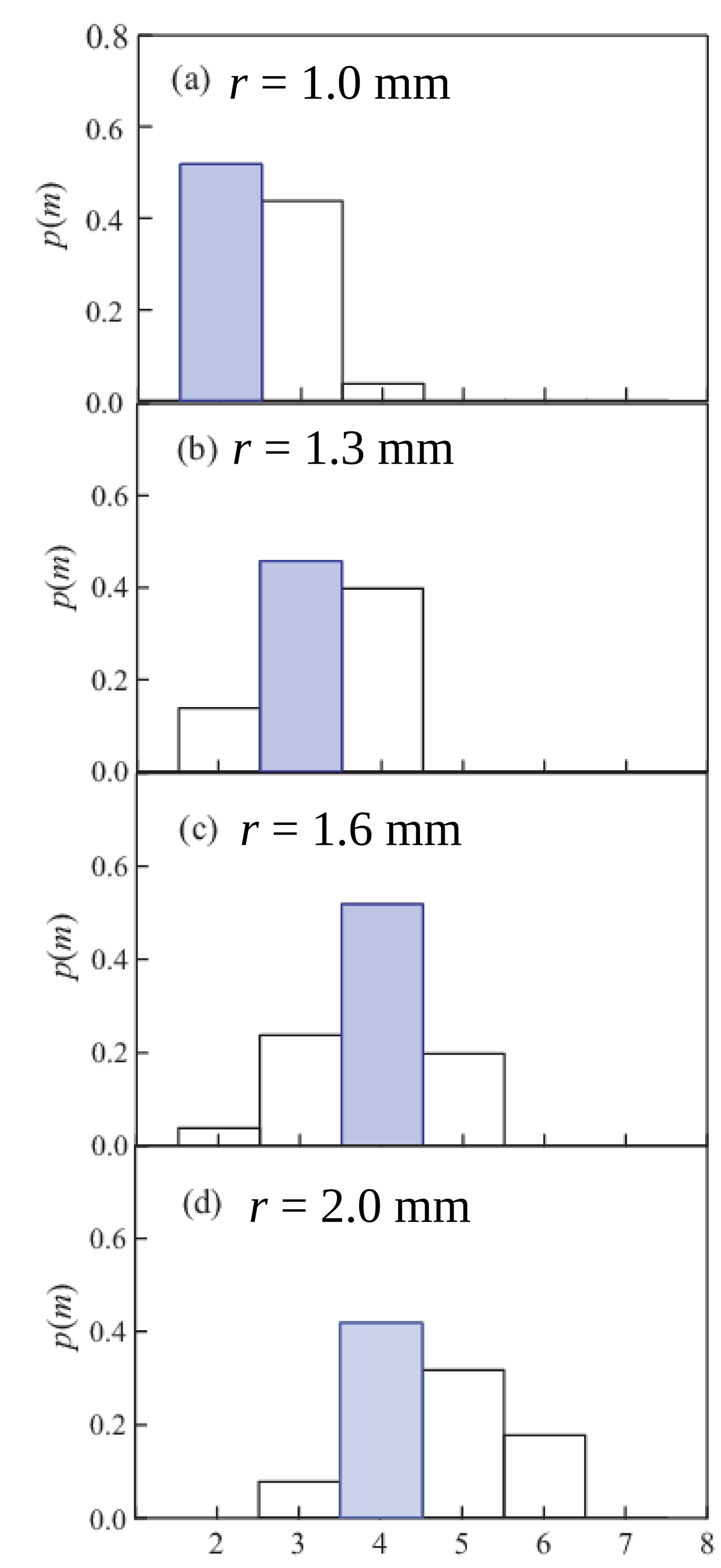
● Probability distribution $p(m)$ with several sample numbers N [2]



$p(m)$ converges with increasing N.

⟶ $p(m)$ with several r is investigated in N=50.

● Probability distribution $p(m)$ with several droplet sizes r [2]



- Peak values of $p(m)$ increase with r and $\Delta\rho$.
- Peak value decreases in an increasing of μ.

Discussion [2]

● Phenomenological model 1

(1) Navier-Stokes equation
(RT instability: Rayleigh-Taylor instability)

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho_2}\nabla P + \nu\nabla^2\mathbf{u} - \frac{\rho-\rho_2}{\rho_2} g\mathbf{e}_z,$$

(2) Diffusion equation

$$\frac{\partial\rho}{\partial t} + \mathbf{u}\cdot\nabla\rho = D\nabla^2\rho,$$

Dimensionless $x' = x/r,\ u' = ur/\nu,\ t' = t\nu/r^2,$
$P' = Pr^2/\rho_2\nu^2,\ \rho' = (\rho-\rho_2)/\rho_2$

(1') Navier-Stokes equation

$$\frac{\partial \mathbf{u}'}{\partial t'} + \mathbf{u}'\cdot\nabla'\mathbf{u}' = -\nabla' P' + u\nabla'^2\mathbf{u}' - G\rho'\mathbf{e}_z,$$

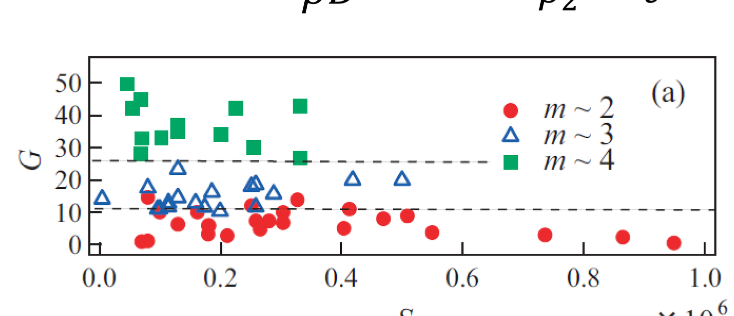
(2') Diffusion equation

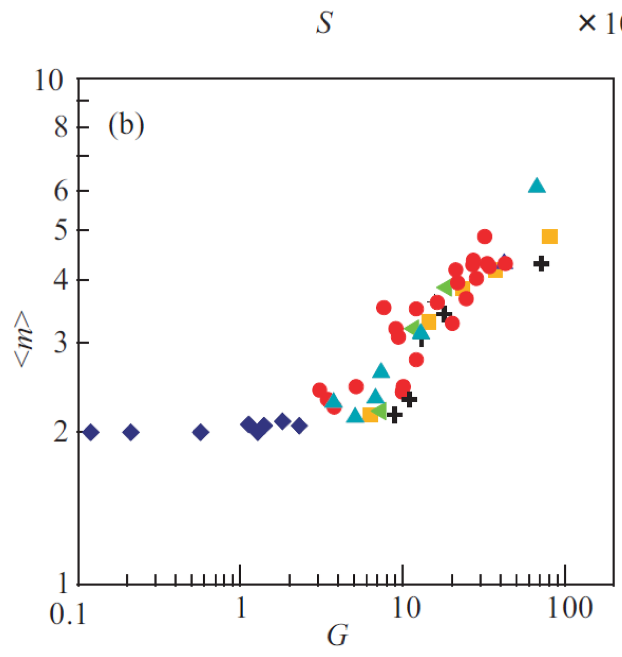
$$\frac{\partial\rho'}{\partial t'} + \mathbf{u}'\cdot\nabla'\rho' = \frac{1}{S}\nabla'^2\rho',$$

***G* is an important factor to determine the mode of the breakup.**

*Nondimensional Parameter

$$S = \frac{\mu}{\rho D} \quad G = \frac{\rho_1-\rho_2}{\rho_2}\frac{gr^3}{\nu^2}$$





We proposed a new phenomenological model

● Navier-Stokes equation

$$\frac{\partial \mathbf{u}'}{\partial t'} + \mathbf{u}'\cdot\nabla'\mathbf{u}' = -\nabla' P' + u\nabla'^2\mathbf{u}' - G\rho'\mathbf{e}_z,$$

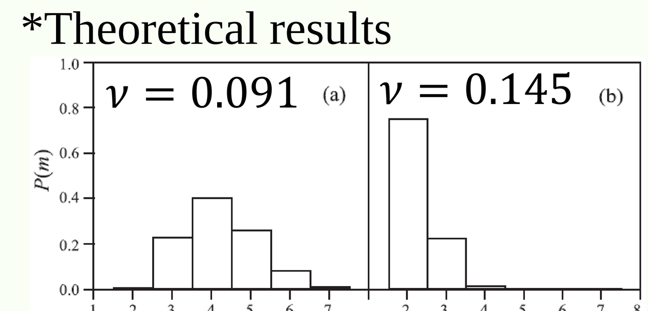
● Expanding of the radius $R(t)$ of the vortex ring

$$R(t) = \sqrt{R(0)^2 + \alpha t},$$

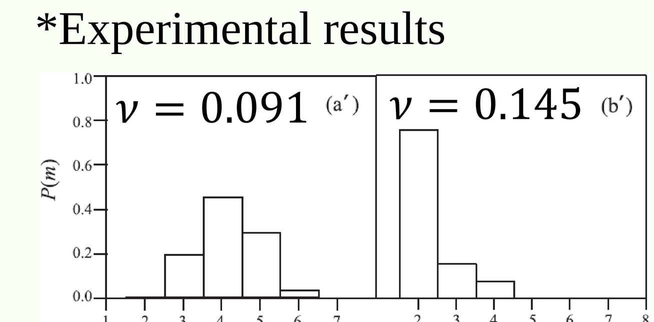
Experimental results provided $\alpha/\nu = (4.3\times10^{-2})G - 0.16$

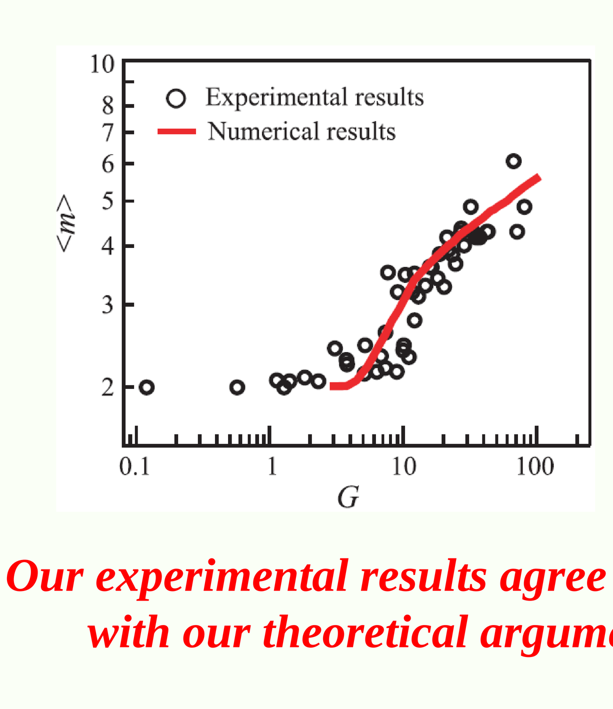
Comparison with experimental results

*Theoretical results



*Experimental results





Our experimental results agree with our theoretical arguments.

Conclusion

- We focused on the breakup of the falling droplet and investigated the numbers of the breakup.
- Our experiments of the probability distributions p(m) agree with those obtained from our phenomenological model.
- (1) RT instability and (2) Expanding of the vortex ring are important factors for the mode selection.