Dynamics of a bubble

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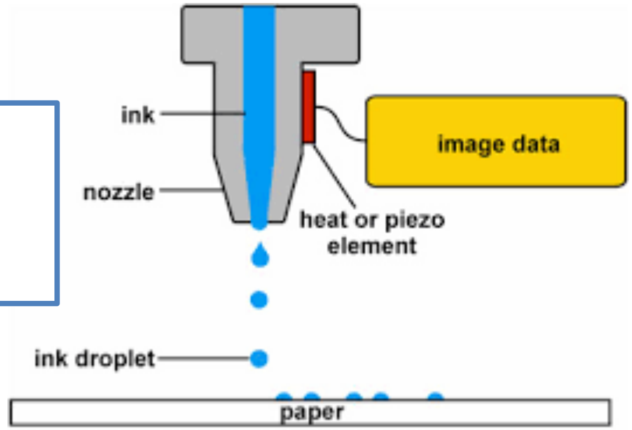
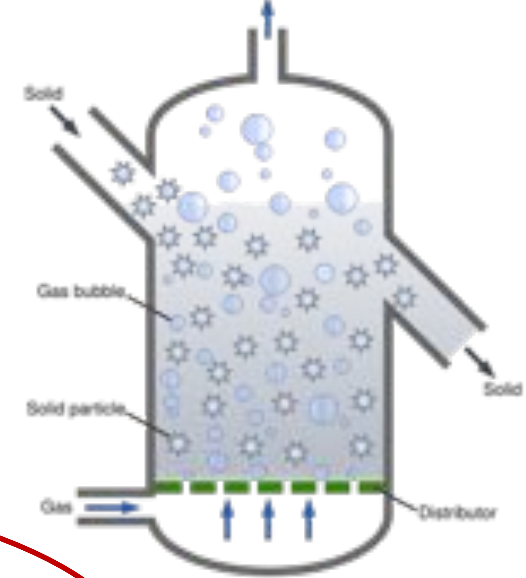
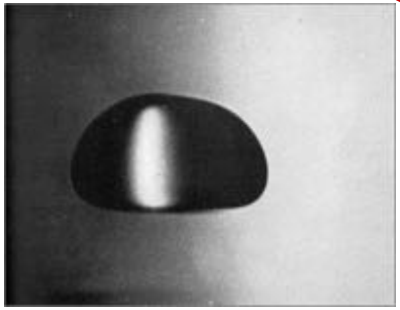
Ink-jet printing



Fluidized bed reactor



Bubbles and drops are not only relevant but also interesting!!



Raindrops

Dolphin Plays With Toroidal bubbles!

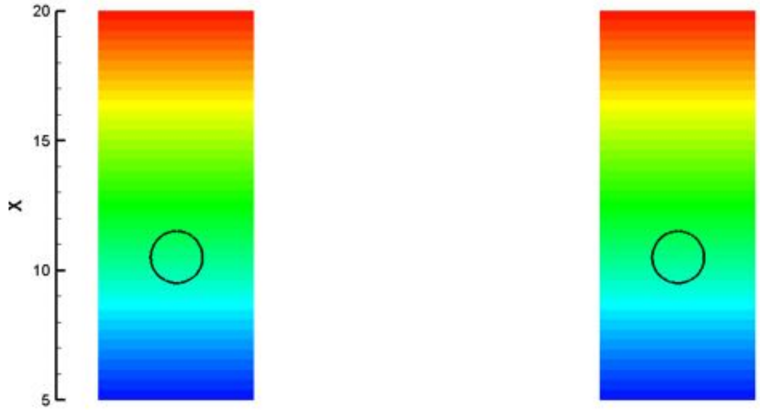
Drops on surfaces

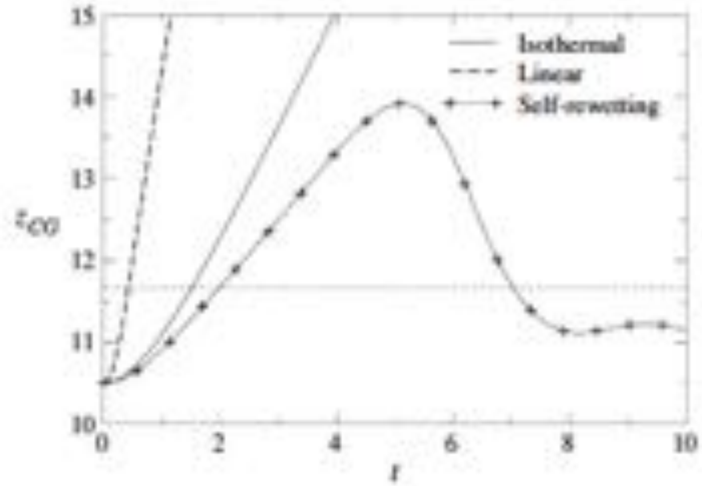
Pictures are taken from different websites in google.

Some peculiar dynamics

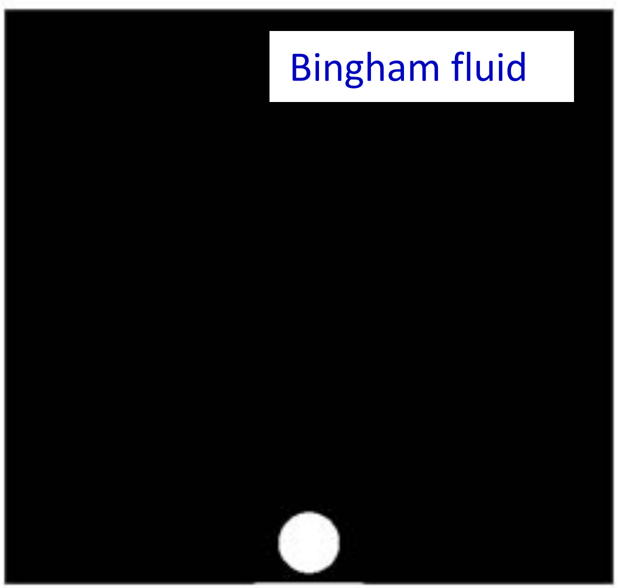
Normal fluids

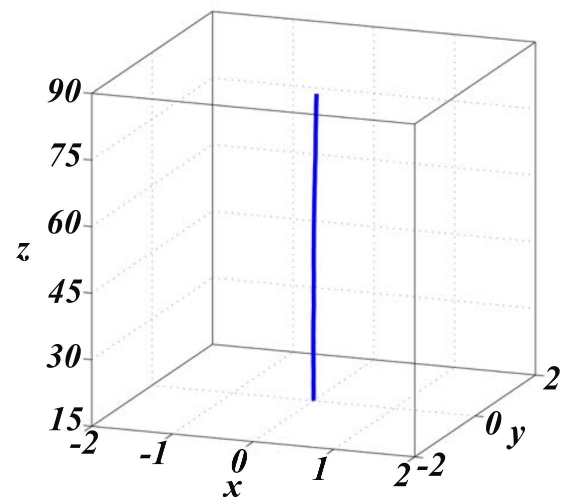
Self-rewetting fluids



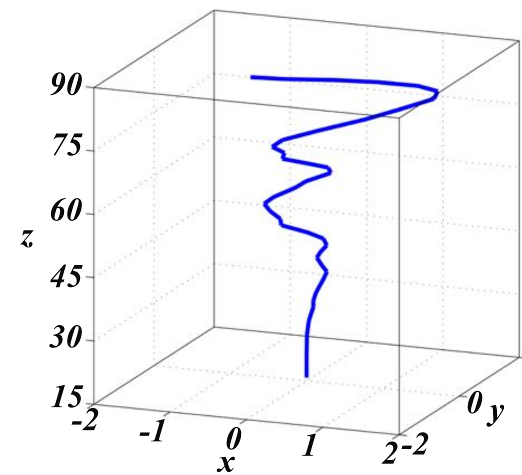


Tripathi *et al.*, JFM, 2015





Normal fluids

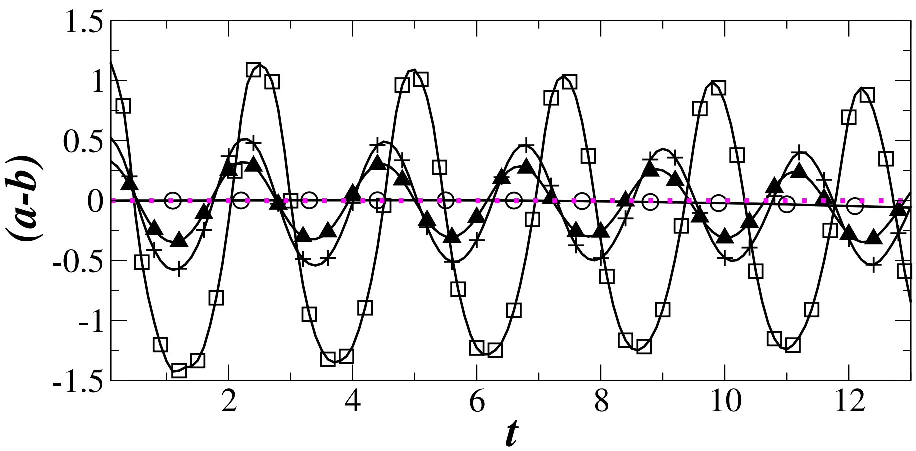


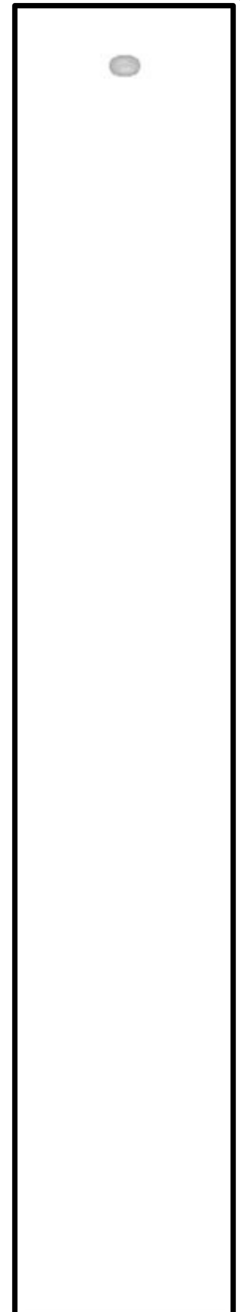
Shear-thinning fluids

Tripathi *et al.*, JNNFM, 2015

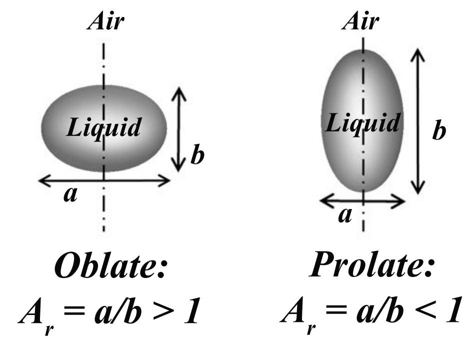
Premlata *et al.*, PoF, 2017

Non-spherical drop





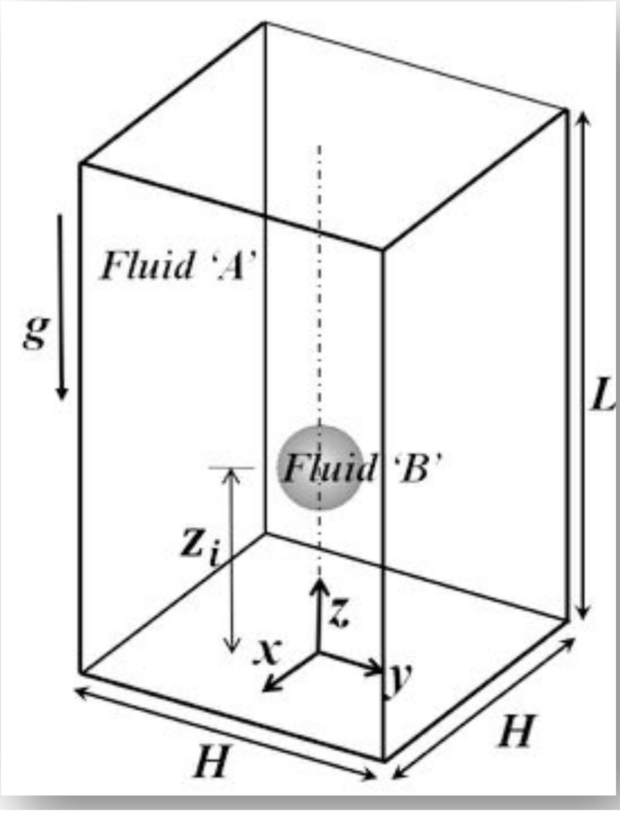
Initially oblate shape drop



Agrawal *et al.*, PRE, 2017

Vortex shedding promotes shape oscillations

Rising bubble



$$Ga \equiv \frac{\rho_A g^{1/2} R^{3/2}}{\mu_A}$$

$$Eo \equiv \frac{\rho_A g R^2}{\sigma}$$

$$\rho_r \equiv \frac{\rho_B}{\rho_A}$$

$$\mu_r \equiv \frac{\mu_B}{\mu_A}$$

- Unconfined:
  No boundary effect
- Initially fluids are stationary
- Isothermal

An additional dimensionless parameter:

$$Mo \equiv \frac{Eo^3}{Ga^4} = \frac{g\mu_B^4}{\rho_B \sigma^3}$$

Governing equations

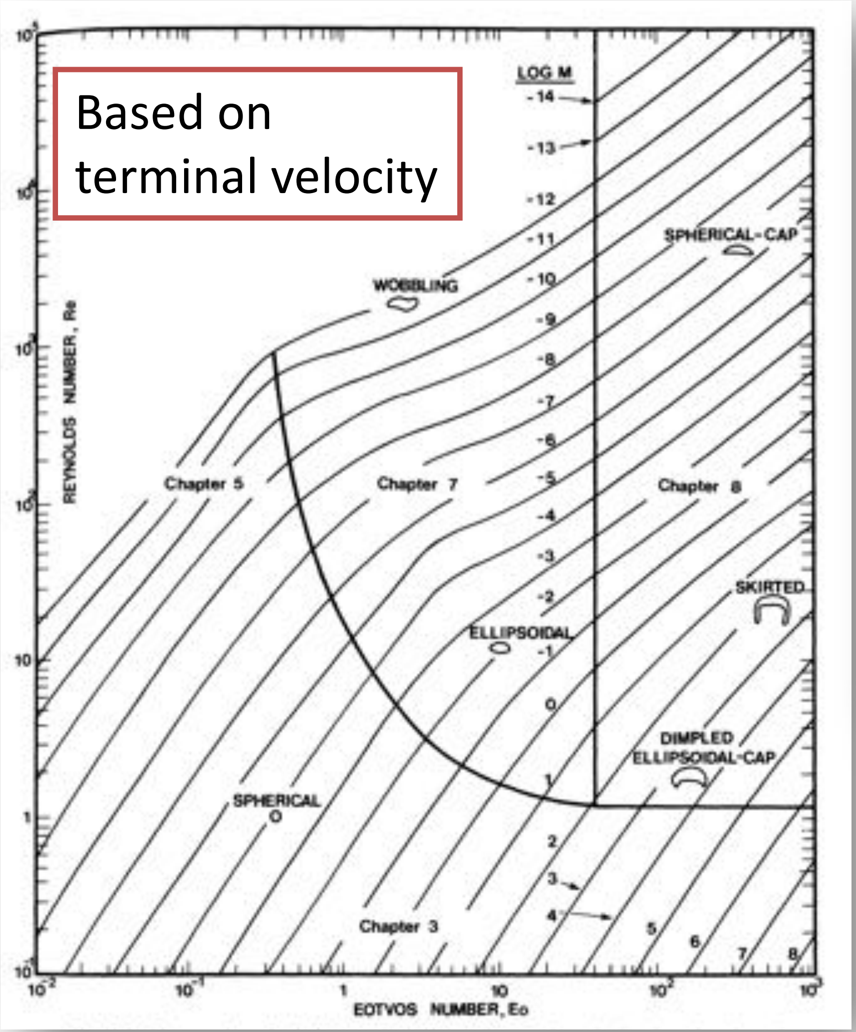
$$
\begin{aligned}
\nabla \cdot \mathbf{u} &= 0 \\
\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} &= -\nabla p + \frac{1}{Ga} \nabla \cdot \left[\mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \right] \\
&+ \delta \frac{\nabla \cdot \mathbf{n}}{Eo} \mathbf{n} - \rho \mathbf{j} \\
\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c &= 0
\end{aligned}
$$

Dimensionless density and viscosity are given by

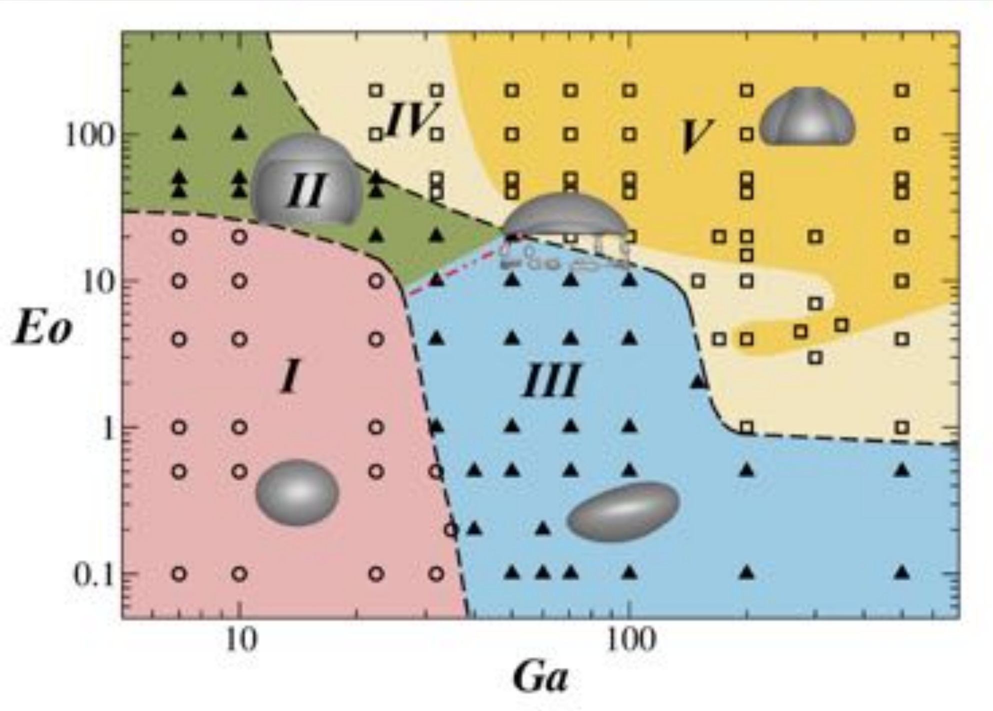
$$
\rho = (1 - c)\rho_r + c
$$

$$
\mu = (1 - c)\mu_r + c
$$

Previous studies



Clift et al. (1978),
Bhaga & Weber, *JFM* 1981
Unbroken bubbles



$$V_s = \sqrt{gR}$$

Tripathi, Sahu & Govindarajan,
Nature Communications, 2015

Several researchers have been working on bubbles and drops from 1500!!

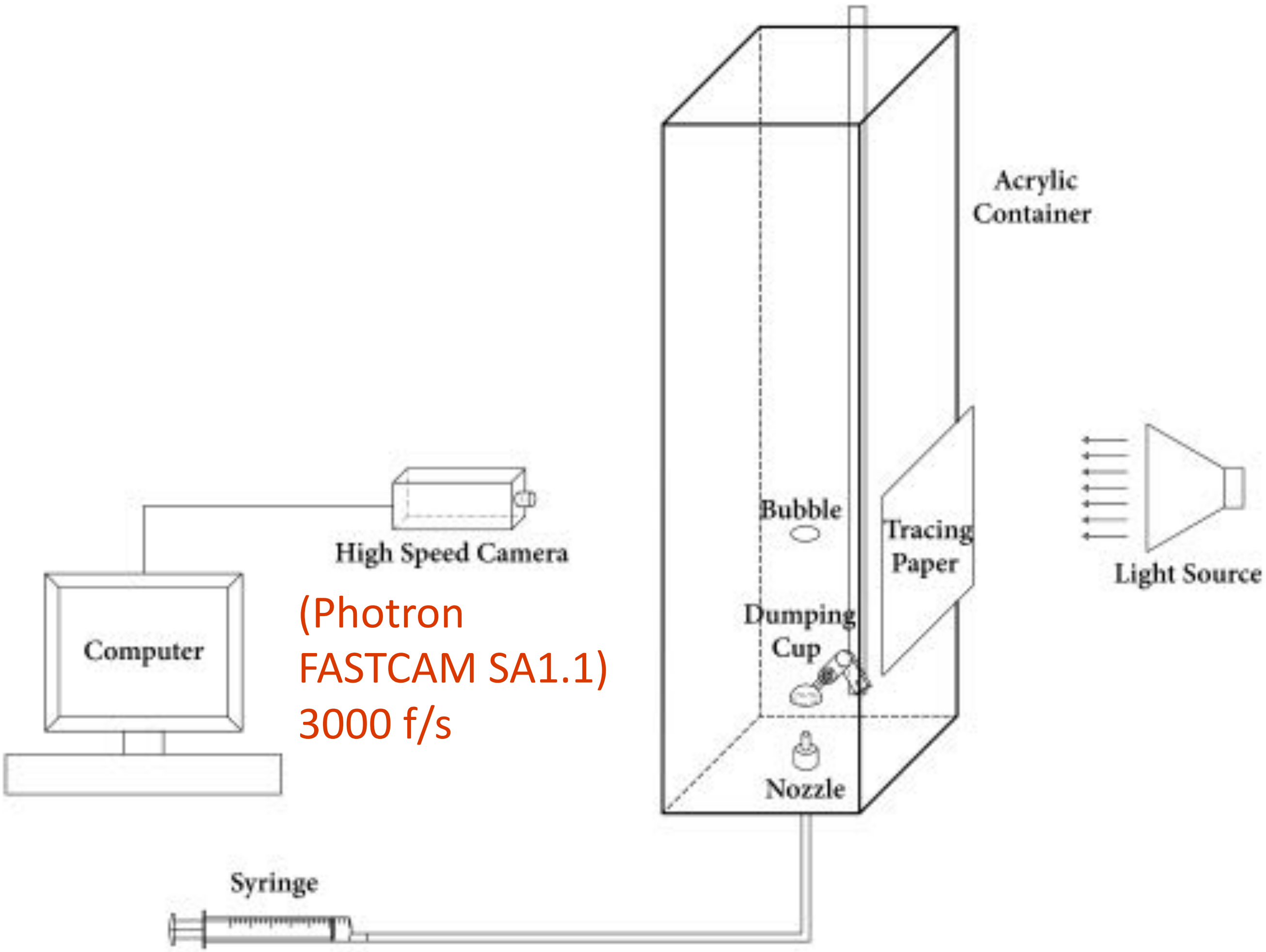
Some results from Tripathi et al. (2015)

A region III bubble
Ga=100, Eo=3

Peripheral break-up
(Ga = 70.7, Eo = 20)
Region IV

Central break-up
(Ga = 70.7,Eo = 200)
Region V

Experimental set-up

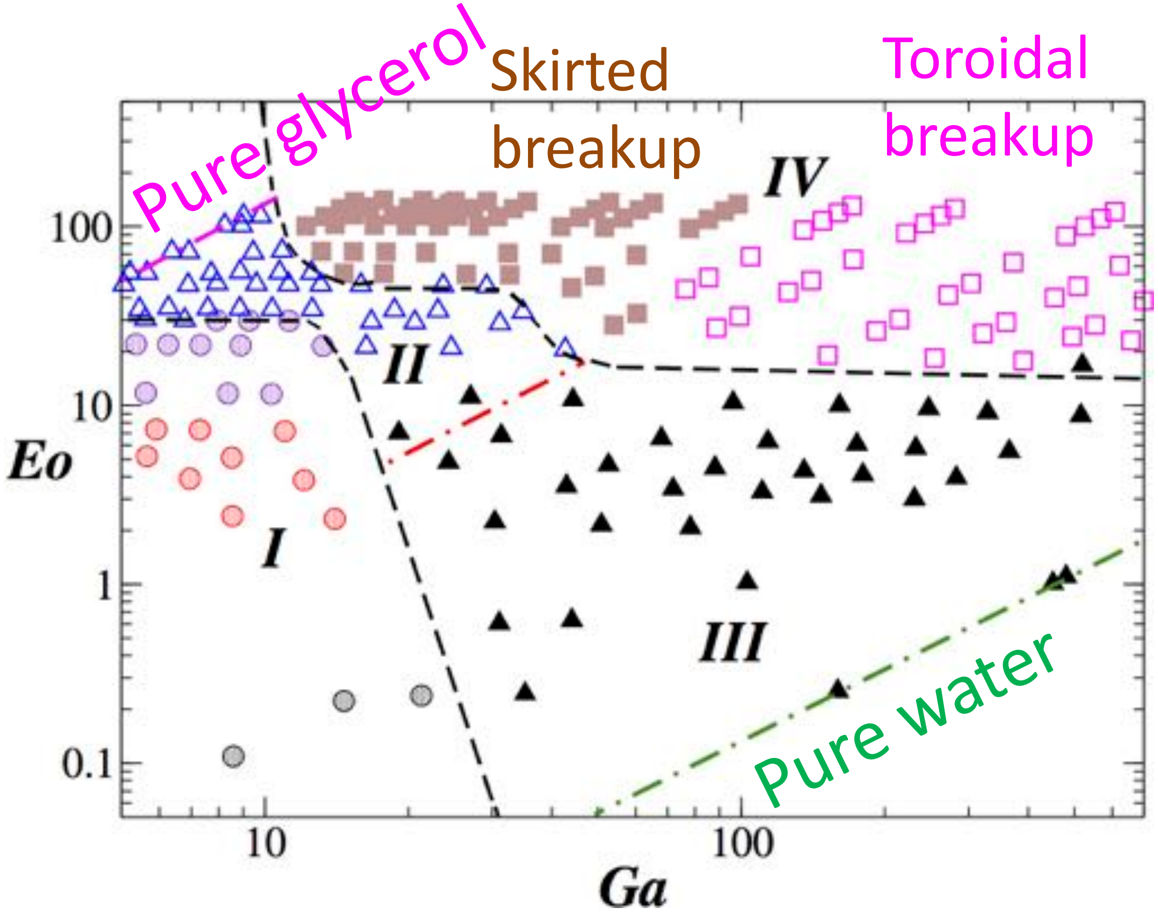


- Close to 300 experiments
- Aqueous solutions of 19 different concentrations of glycerol
- Smallest bubble: R=1.4 mm
- Biggest bubble: R=26.7 mm

Fluid properties of the water-glycerol mixtures

Sample number	% of Glycerol	μ_0 $(Pa.s)$	ρ_0 (Kg/m^3)	σ (mN/m)	Mo
1	100	1657	1260	62.1	230.314
2	99.8	1524	1259	62.2	163.38
3	98.2	1115	1256	62.3	46.48
4	97	967.8	1254	62.4	28.259
5	96	797	1249	62.6	12.9
6	94.8	681	1246	62.8	6.83
7	93.7	581	1243	63.0	3.6
8	92.2	478	1241	63.1	1.6
9	90.8	319.7	1235	63.4	0.3256
10	88.5	258	1230	63.6	0.1372
11	85	170	1222	64.2	0.0253
12	80	96.9	1209	64.8	0.00263
13	70	57.8	1182	65.8	0.000324
14	60	26	1154	66.6	1.315×10^{-5}
15	50	15.1	1127	67.5	1.5×10^{-6}
16	40	9.6	1100	68.4	2.4×10^{-7}
17	25	7	1061	69.5	6.57×10^{-8}
18	10	4.3	1023	69.8	9.56×10^{-9}
19	Pure water	1	1000	72.8	2.52×10^{-11}

Phase diagram



Region I: Axisymmetric
Region II: Skirted
Region III: Wobbling
Region IV: Breakup

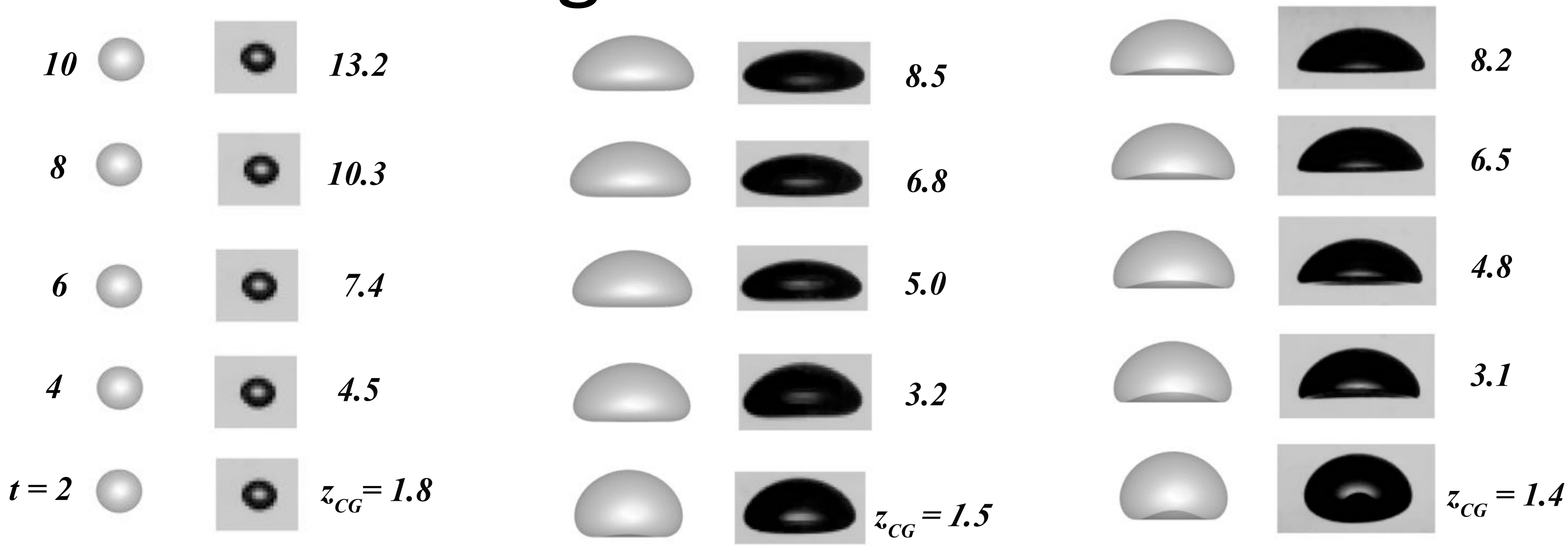
Comparison with Tripathi *et al.* (2015):

Central breakup (Region V) is not observed

Possible reasons:

- Non-spherical shape
- The actual density and viscosity ratios
- Change in surface properties due to experimental conditions: Contaminations

Region I bubbles

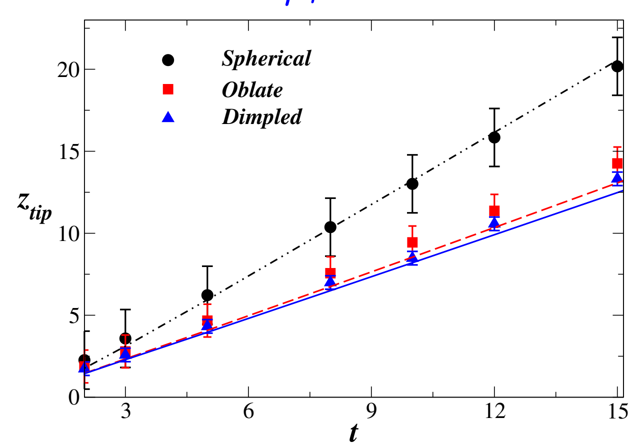


Spherical
40% of glycerol
Radius: 0.83 mm
$\mu_r = 1.04 \times 10^{-3}$,
$\rho_r = 9.09 \times 10^{-4}$

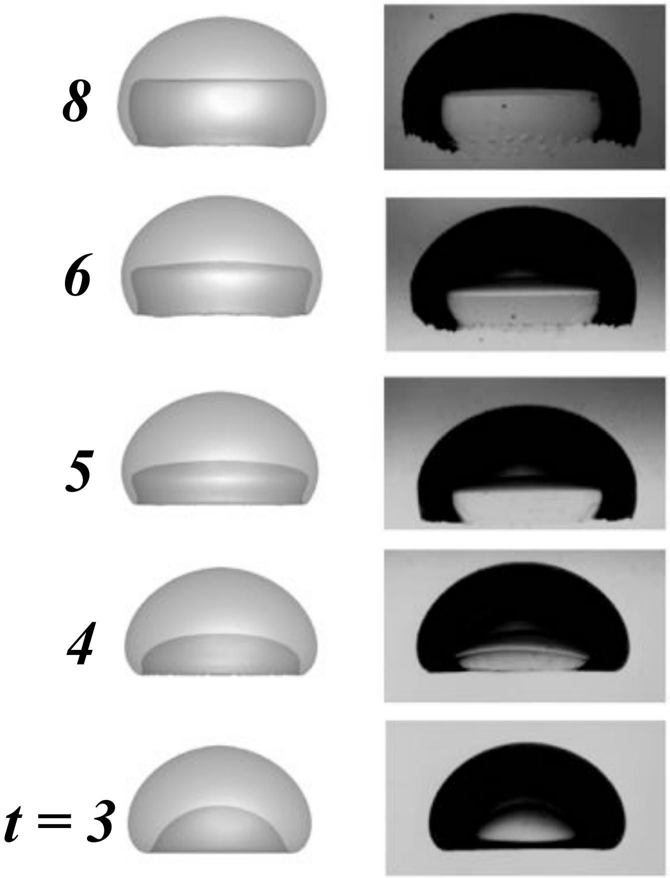
Oblate
85% of glycerol
5.2 mm
$\mu_r = 5.9 \times 10^{-5}$,
$\rho_r = 8.2 \times 10^{-4}$

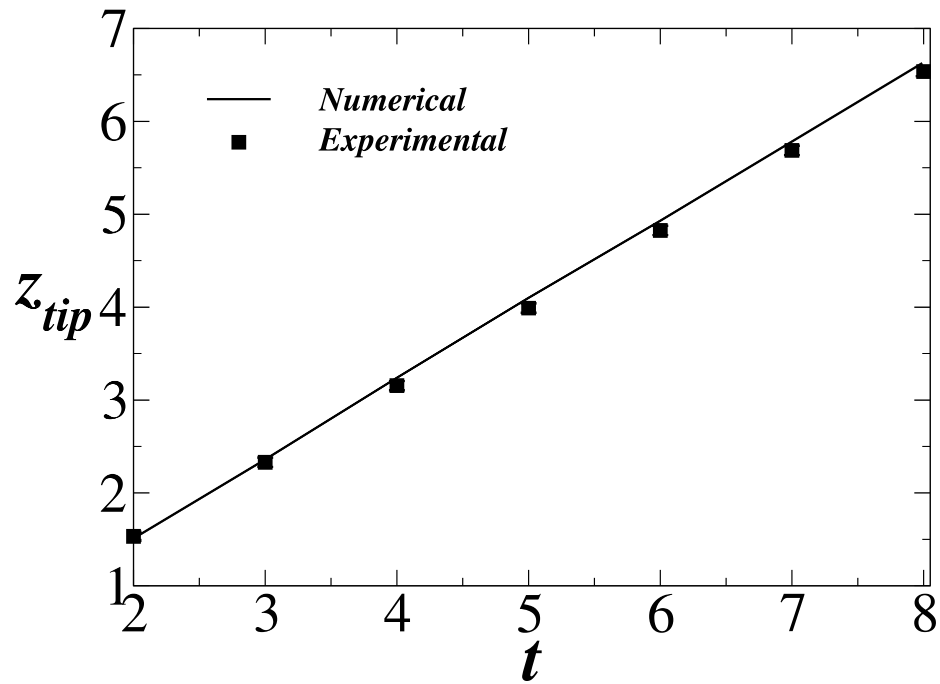
Dimpled
90.8% glycerol
7.8 mm
$\mu_r = 3.13 \times 10^{-5}$,
$\rho_r = 8.1 \times 10^{-4}$

This agrees with Clift *et al.* (1978) and Tripathi *et al.* (2015)



Region II bubbles

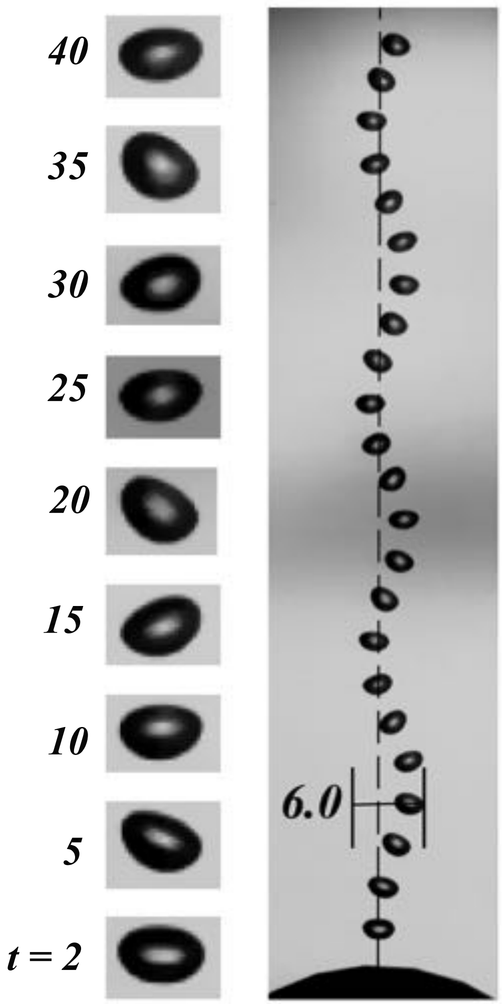




97% of glycerol
Radius: 19.27 mm

$\mu_r = 1.03 \times 10^{-5}$,
$\rho_r = 7.97 \times 10^{-4}$

Region III bubble



25% of glycerol

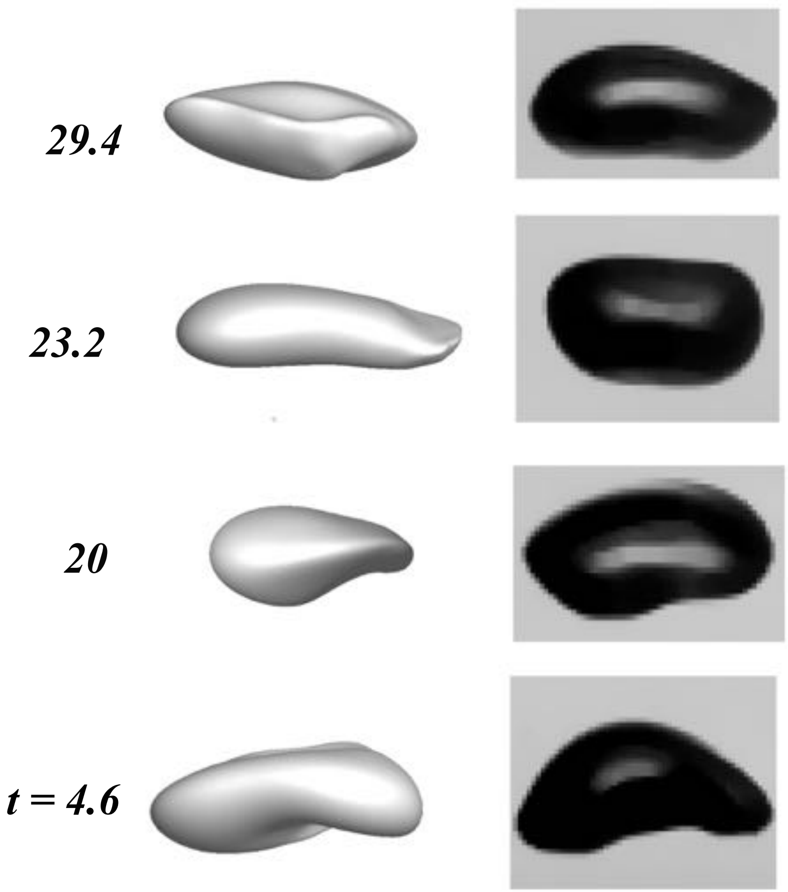
Radius: 2 mm

$\mu_r = 1.43 \times 10^{-3}$,

$\rho_r = 9.43 \times 10^{-4}$

$Ga = 44.06, Eo = 0.68$

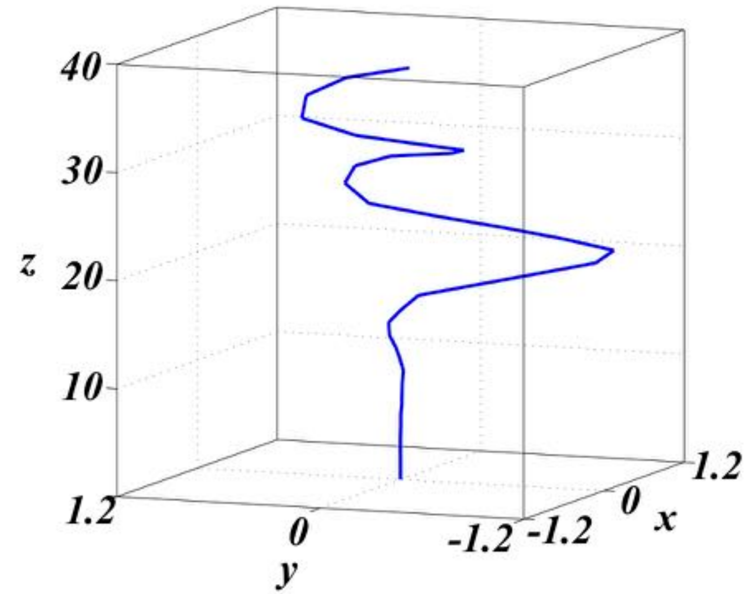
Another Region III bubble



10% of glycerol
Radius: 4.57 mm

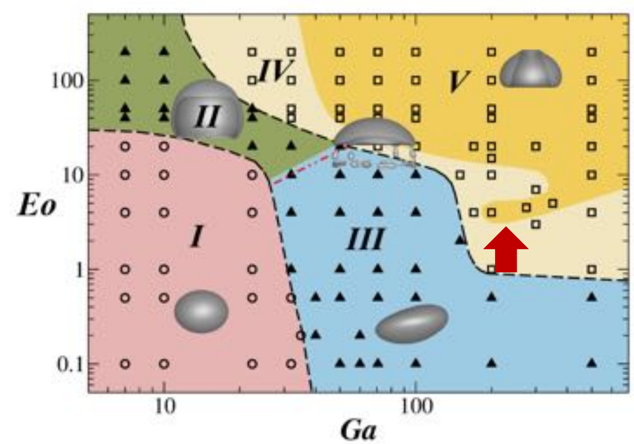
$\mu_r = 2.33 \times 10^{-3}, \rho_r = 9.78 \times 10^{-4}$

$Ga = 230.8, Eo = 3$

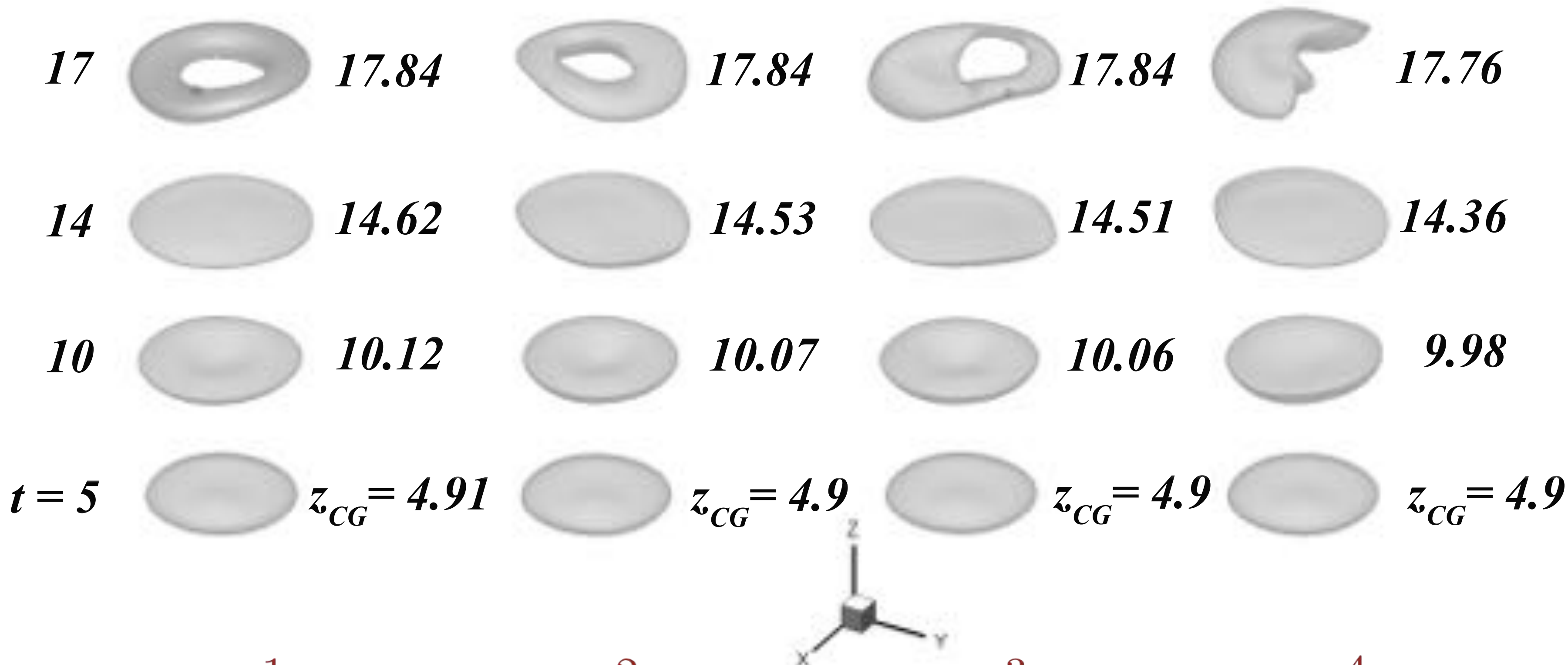


This bubble falls in region IV of Tripathi *et al.* (2015)

$\mu_r = 10^{-2}, \rho_r = 10^{-3}$



Effect of viscosity ratio

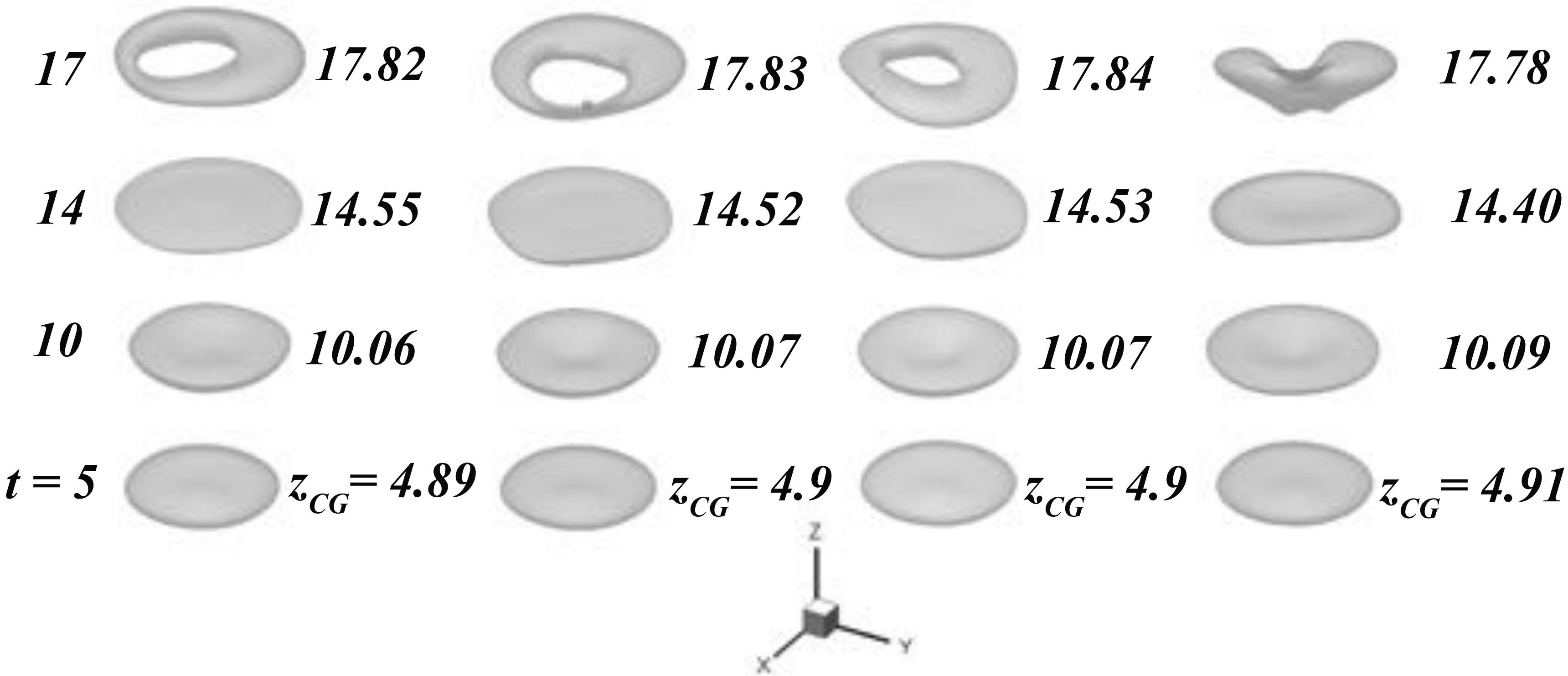


$\mu_r = 10^{-1}$ $\quad 10^{-2}$ $\quad 10^{-3}$ $\quad 10^{-4}$

$Ga = 230.8, Eo = 3$

$\rho_r = 10^{-3}$

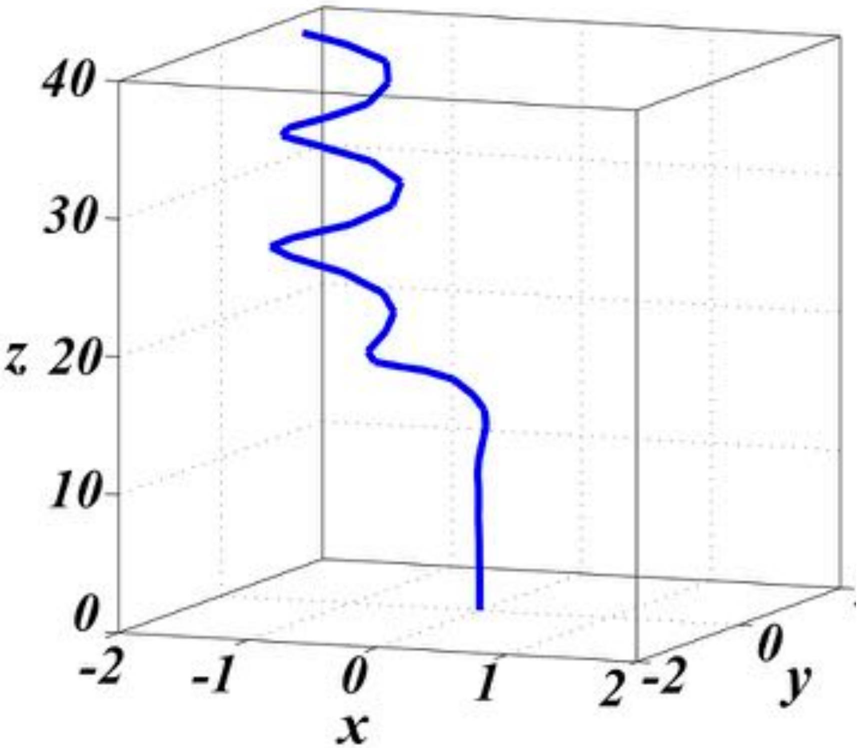
Effect of density ratio



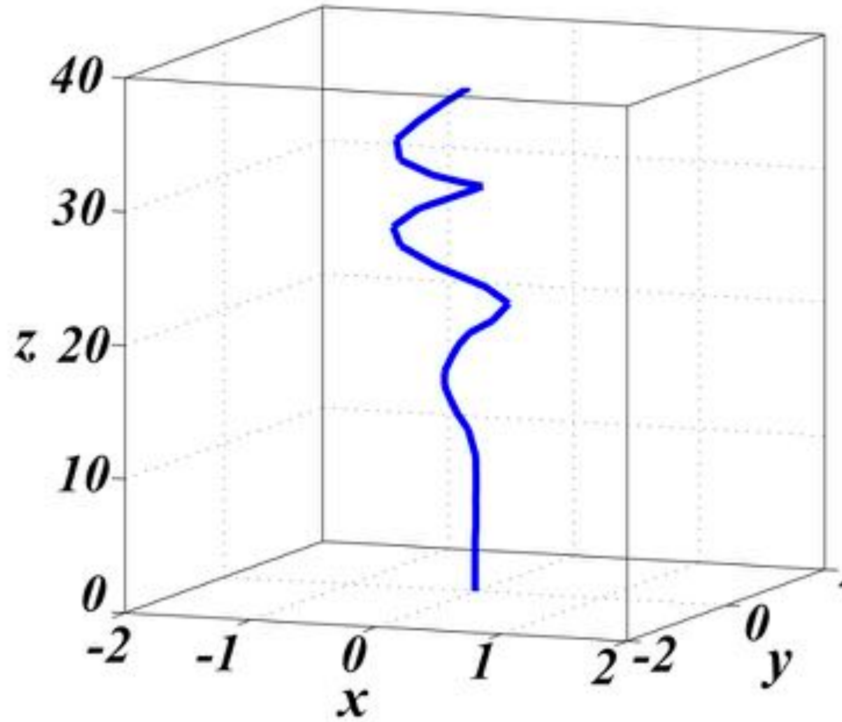
$\rho_r = 10^{-1}$ $\quad 2 \times 10^{-3}$ $\quad 10^{-3}$ $\quad 10^{-4}$

$Ga = 230.8, Eo = 3$
$\mu_r = 10^{-2}$

Trajectories



$\mu_r = 10^{-4}, \rho_r = 10^{-3}$



$\mu_r = 10^{-2}, \rho_r = 10^{-4}$

Break-up bubbles

70% of glycerol
Radius: 22.8 mm
$\mu_r = 1.73 \times 10^{-4}$,
$\rho_r = 8.46 \times 10^{-4}$

8

7

6

5

t = 4

80% of glycerol
Radius: 26.7 mm
$\mu_r = 5.9 \times 10^{-5}$,
$\rho_r = 8.27 \times 10^{-4}$

Concluding remarks

- The dynamics of a rising bubble in aqueous solutions of glycerol is investigated experimentally. Close to 300 bubbles are studied.
- A phase plot in *Ga* - *Eo* plane is generated, which shows different regions in terms of bubble behavior, namely, axisymmetric, skirted, spiraling and breakup.
- Apart from Reynolds and Eotvos numbers, which were thought to be the only governing parameters for rising bubbles in air-liquid systems, our results show that the dynamics is also influenced by the actual density and viscosity ratios.
- The present result provides an useful extension to the classical region map of Bhaga and Weber (1981) and Clift *et al.* (1978).

Thank you