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EXPERIMENTAL INVESTIGATION OF LIQUID DROPLET BREAK-UP DURATION

(Submitted to ASME Cavitation Forum, 1977)

by

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INTRODUCTION

The problem which is herewith presented concerns the kinematics of deformation and disintegration of liquid droplets in a gas stream. A liquid droplet being present in a gas stream will break up due to aerodynamic forces if the Weber Number is higher than the critical value. The critical Weber Number has been investigated and published by several authors, for instance, Lane (1), Hinze (2), Hanson, Domich, Adams (3), Wolynskij (4) and others. Thus it is well known. However, the authors' interest was to measure the life of liquid droplets before break up. Several authors have suggested many different semi-theoretical formulae for estimation of the break-up duration. Because the formulae were not reliable, experimental investigation seemed to be necessary and interesting as well. The first experimental results concerning water droplets were published by Hassler according to ref. (5). They included in their study several other liquids such as methylene, ethylene, buthylene and glycerine.

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The approach to this problem is as follows, based on mass conservation:

For the gas flow

$$\frac{\partial \rho_g}{\partial t} + \text{div}\,(\rho_g \vec{V}_g) = 0 \qquad (1)$$

$$\rho_g \frac{d V_g}{dt} = \text{div}\,\vec{P}_g \qquad (2)$$

For the liquid flow

$$\text{div}\,\vec{V}_l = 0 \qquad (3)$$

$$\rho_l \frac{d\vec{V}}{dt} = \rho_l g + \text{div}\,\vec{P}_l \qquad (4)$$

and for boundary conditions

$$(P_g)_b^n + \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = (P_l)_b^n \qquad (5)$$

(normal stress)

$$(\tau_g)_b^t = (\tau_l)_b^t \qquad (6)$$

(stress)

$$(V_g)_b = (V_l)_b \qquad (7)$$

(velocity)

A set of dimensionless parameters was formed. As a result of the dimensionless analysis which has been done for incompressible, steady flow, neglecting the gravity forces and heat transfer, we obtained several parameters important to the process.

$$We = \frac{\rho_g \cdot V^2 \cdot d}{\sigma} \qquad (8)$$

(Weber Number)

$$Str = \frac{V \cdot t}{d} \qquad (9)$$

(Strouhal Number)

$$La = \frac{\mu_l^2}{\sigma \cdot d \cdot \rho_l} \qquad (10)$$

(Laplace Number)

$$\frac{\mu_l}{\mu_g} \qquad (11)$$
(ratio of viscosity)

$$\frac{\rho_l}{\rho_g} \qquad (12)$$
(ratio of density)

$$\frac{V}{V_g} \qquad (13)$$
(ratio of velocity)

$$\frac{\bar{V}'^2_g}{\bar{V}^2_g} \qquad (14)$$
(ratio of turbulence)

For a droplet drifting freely in a flow the velocity ratio is unnecessary. In the experiment the ratios of density and ratio of turbulence have been neglected ($\frac{\rho_l}{\rho_g} \approx$ const, the ratio of turbulence was not controlled.

EXPERIMENTAL FACILITY AND APPARATUS

The facility is shown in the sketch (Fig. 1). A wind tunnel and droplet generator were used. Liquid particles dropping into the stream were disintegrated. The air velocity and droplet diameter were controlled. The velocity profile was almost uniform across the stream, since the boundary layer thickness was not more than 1.5 mm.

The mechanism of droplet deformation and disintegration was investigated by means of a photo camera and spark flash. The flash duration ($\sim 1\ \mu s$) proved suitable for the purpose. The droplet deformation measurement was rather simple. Droplets entrained in the air stream cut the laser beam. The signal passes through the photo-cell, indicating the beginning of the process, and causing the spark-flash to fire ~ 2 ms later. The delay (time between the initiation of droplet signal and the light flash) was regulated. By changing the delay time, there was the possibility of taking several pictures for different stages of the droplet break-up process. Typical pictures are shown in Fig. 2.

RESULTS OF THE EXPERIMENT

Typical mechanisms of liquid droplet deformation and disintegration are presented, for the selected cases corresponding to the pictures in Fig. 2, on the graph (Fig. 3). The ratio of deformation has been defined by the ratio of dimensions $\frac{d}{d_o}$ and $\frac{h}{d_o}$.

The form of the deformation is the following: At first a liquid disc is formed, which takes a relatively long time. Thereafter the velocity of deformation increases rapidly, and the disc becomes a hollow sphere. The life of this "bubble" is relatively short. A particular case was described above. The precise forms change according to the condition of the flow.

Droplet break-up time was also studied for several conditions (Table 1).

Time of break-up has been shown as a function of the Weber Number (Fig. 4). While the lower curve shows the beginning of disintegration (Fig. 2f), the upper one concerns the finish (Fig. 2h).

Similar results which have been obtained for other liquids are shown in Fig. 5 (the beginning of disintegration), and Fig. 6 (the end). The curves are qualitatively similar, but there is a significant quantitative difference.

CONCLUSIONS

1. Droplet break-up duration depends on the Weber Number. This is a very strong relationship.

2. There is no strong influence of viscosity for the conditions studied, eg., while viscosity increases by $\sim 10^3$, break-up duration increases only twice. We would expect the duration to increase more rapidly for higher viscosities than used in this experiment.

3. Break-up duration cannot be estimated using the formula of Engels and Littnay from ref. (5). This formula, based on natural droplet frequency ($t = \frac{d^3 \cdot \rho_l}{\sigma}$) gives quite different results. The difference is 2-3 orders of magnitude when compared to the present experiment.

List of Symbols

d - droplet diameter

g - gravity acceleration

p - pressure

t - time

V - velocity

μ - viscosity

ρ - density

σ - surface tension

τ - surface stress

Δt, ΔWe - experimental errors of break-up duration and Weber Number (see Figs. 5 and 6)

h - deformed droplets dimension parallel to axis, d is assumed normal to axis.

Indexes

g - gas

l - liquid

o - initial condition

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APPENDIX - BOUNDARY CONDITIONS

gas flow

$$\frac{\partial \rho_g}{\partial t} + div\left(\rho_g \vec{V}_g\right) = 0 \qquad (1)$$

$$\rho_g \frac{d\vec{V}_g}{dt} = div \cdot \bar{P}_g \qquad (2)$$

liquid flow

$$div\ \vec{V}_l = 0 \qquad (3)$$

$$\rho_l \frac{d\vec{V}_l}{dt} = \rho_l \vec{g} + div\ \bar{P}_l \qquad (4)$$

boundary conditions

$$\left(p_g\right)_b^n + \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = \left(P_l\right)_b^n \qquad (5)$$

$$\left(\tau_g\right)_b^t = \left(\tau_l\right)_b^t \qquad (6)$$

$$\left(\bar{V}_g\right)_b = \left(V_l\right)_b \qquad (7)$$

List of Figures

REFERENCES

1. Lane, W. R., "Fundamentals of the Hydrodynamics Mechanism of Splitting in Dispersion Processes".

2. Hinze

3. Hanson, A. R., Domich, E. G., Adams, M. S., "Shock Tube Investigation of the Breakup of Drops by Air Blasts", The Physics of Fluids, 1964, Vol. 6, No. 8.

4. Wolynskij, M. S., "Droplet Splitting in Air Stream", Dokl A.S. USSR, Vol. 62, No. 3.

5. Gardner, G. C., "Events Leading to Erosion in the Steam Turbine", Proc. Inst. Mech. Engrs., Vol. 178, No. 23.

Table 1

Experiment conditions

Properties ↓ / Liquid →		methylen CH_3OH	water H_2O	ethylen C_2H_5OH	buthylen C_4H_9OH	glycerine $C_3H_8O_3$
μ_l	$\frac{kg}{m \cdot s}$	$0{,}578 \cdot 10^{-3}$	$0{,}892 \cdot 10^{-3}$	$1{,}243 \cdot 10^{-3}$	$2{,}35 \cdot 10^{-3}$	$1020 \cdot 10^{-3}$
ρ_l	$\frac{kg}{m^3}$	$0{,}792 \cdot 10^{3}$	10^{3}	$0{,}796 \cdot 10^{3}$	$0{,}810 \cdot 10^{3}$	$1{,}234 \cdot 10^{3}$
σ	$\frac{kg}{s^2}$	$22{,}6 \cdot 10^{-3}$	$72 \cdot 10^{-3}$	$22{,}8 \cdot 10^{-3}$	$24{,}6 \cdot 10^{-3}$	$57{,}11 \cdot 10^{-3}$
d_o	mm	4,7	5,6	4,7	4,7	5,0
$\frac{\mu_l^2}{\sigma \rho_l d_o}$	—	$0{,}398 \cdot 10^{-5}$	$0{,}240 \cdot 10^{-5}$	$1{,}82 \cdot 10^{-5}$	$9{,}80 \cdot 10^{-5}$	2,95
$\frac{\mu_l}{\mu_g}$	—	31	48	67	159	$55 \cdot 10^{3}$
V	m/s	14,1	14,1	14,1	14,1	18,1
$P_{dyn} = \frac{\rho_g V^2}{2}$	$\frac{N}{m^2}$	125	125	125	125	205
$We = \frac{\rho_g V^2 d_o}{\sigma}$	—	51	19,5	50,5	48	36
V	m/s	20	19,5	20	20	27
$P_{dyn} = \frac{\rho_g V_o^2}{2}$	$\frac{N}{m^2}$	245	235	245	245	445
$We = \frac{\rho_g V^2 d_o}{\sigma}$	—	101,5	36,5	100,5	93	78
V	m/s	25	26,5	25	27,5	32
$P_{dyn} = \frac{\rho_g V^2}{2}$	$\frac{N}{m^2}$	390	440	390	470	645
$We = \frac{\rho_g V^2 d_o}{\sigma}$	—	163	80,5	162	180	113

gas: air

$p \cong 1.014 \cdot 10^5 \frac{N}{m^2}$

$T = 20\,^\circ C$

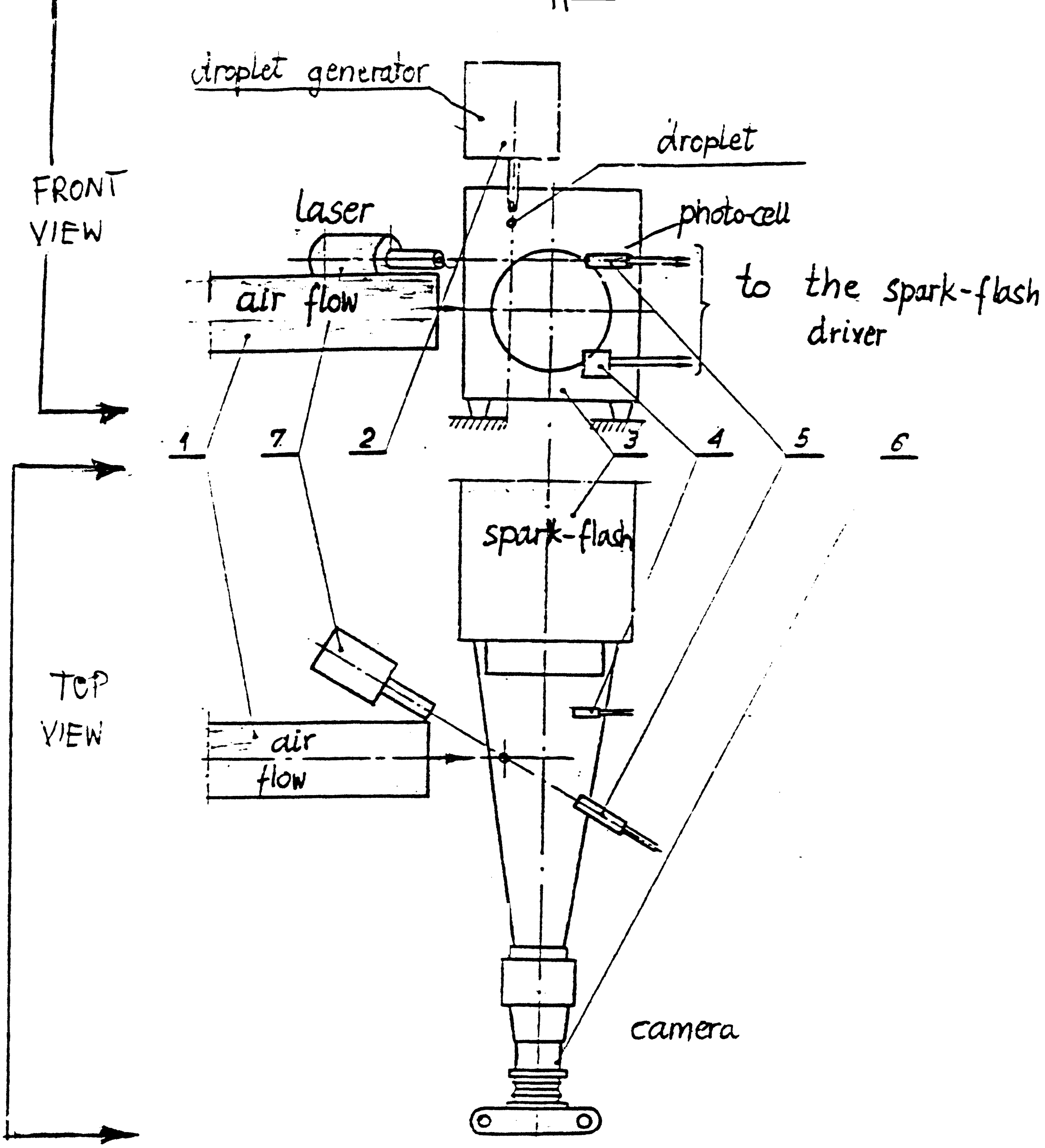


Fig. 1

Experimental Facility
(Flow Direction: Left to Right)

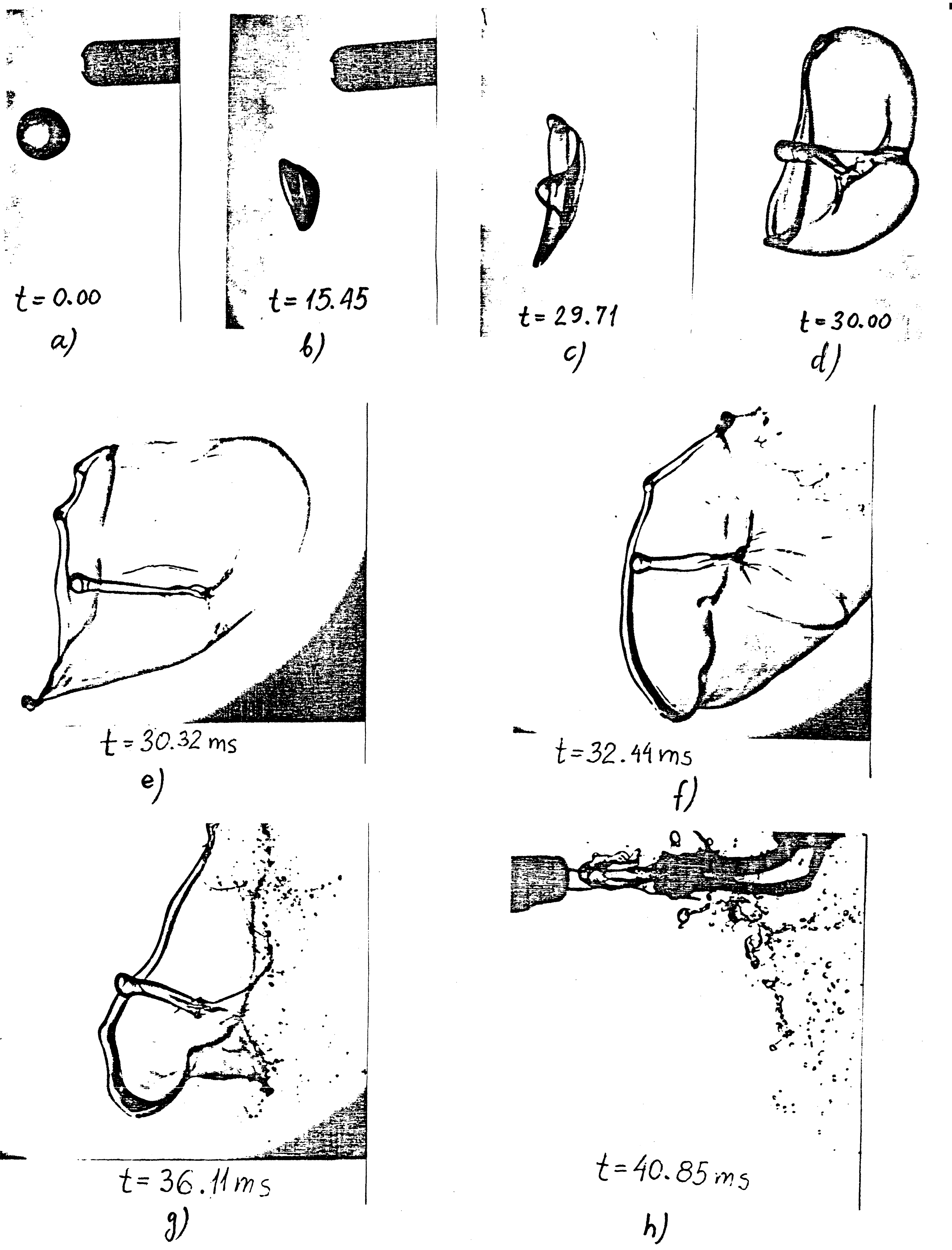
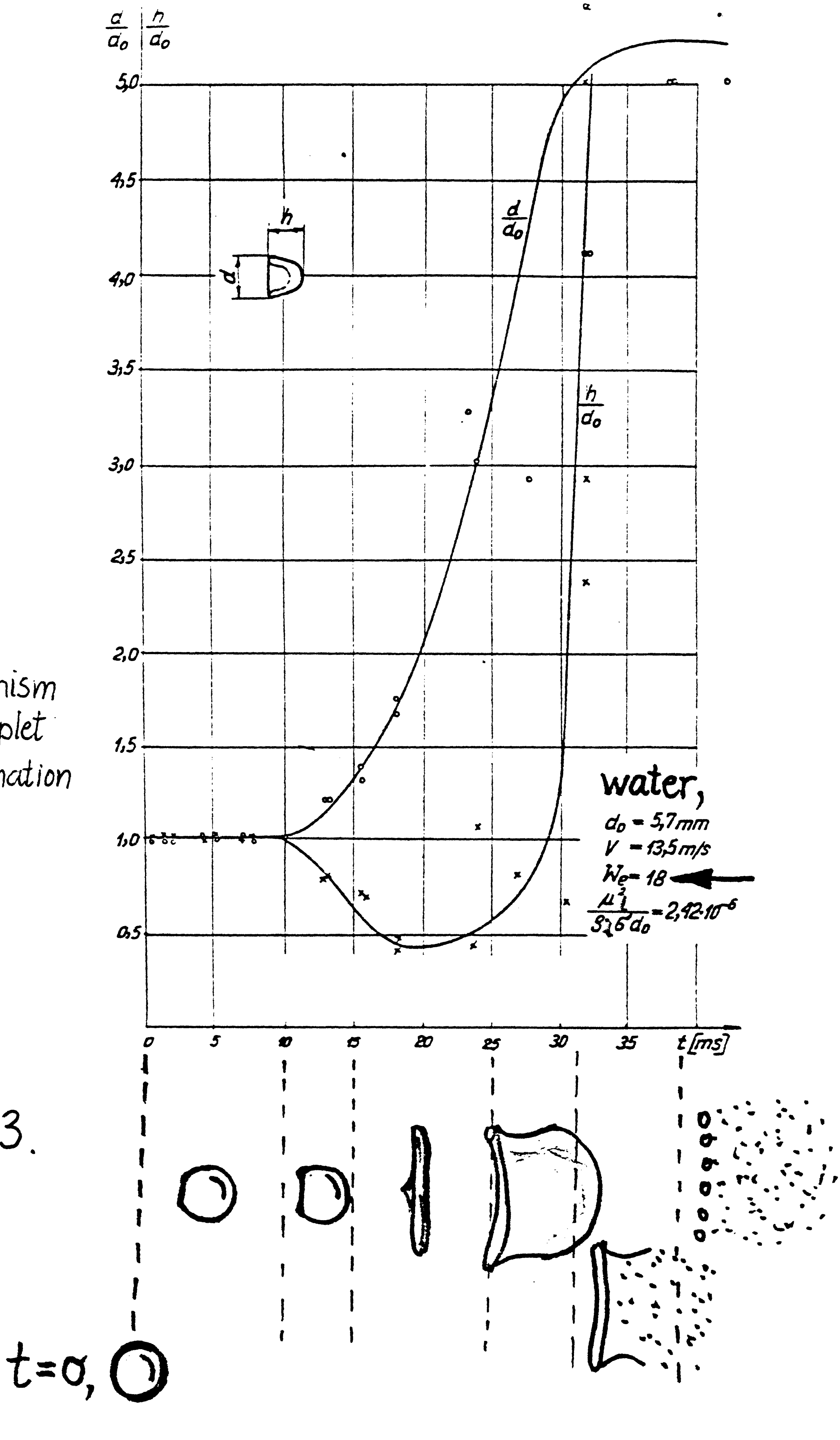

t = 0.00
a)
t = 15.45
b)
t = 29.71
c)
t = 30.00
d)
t = 30.32 ms
e)
t = 32.44 ms
f)
t = 36.11 ms
g)
t = 40.85 ms
h)

Fig. 2.



Mechanism of droplet deformation

Fig.3.

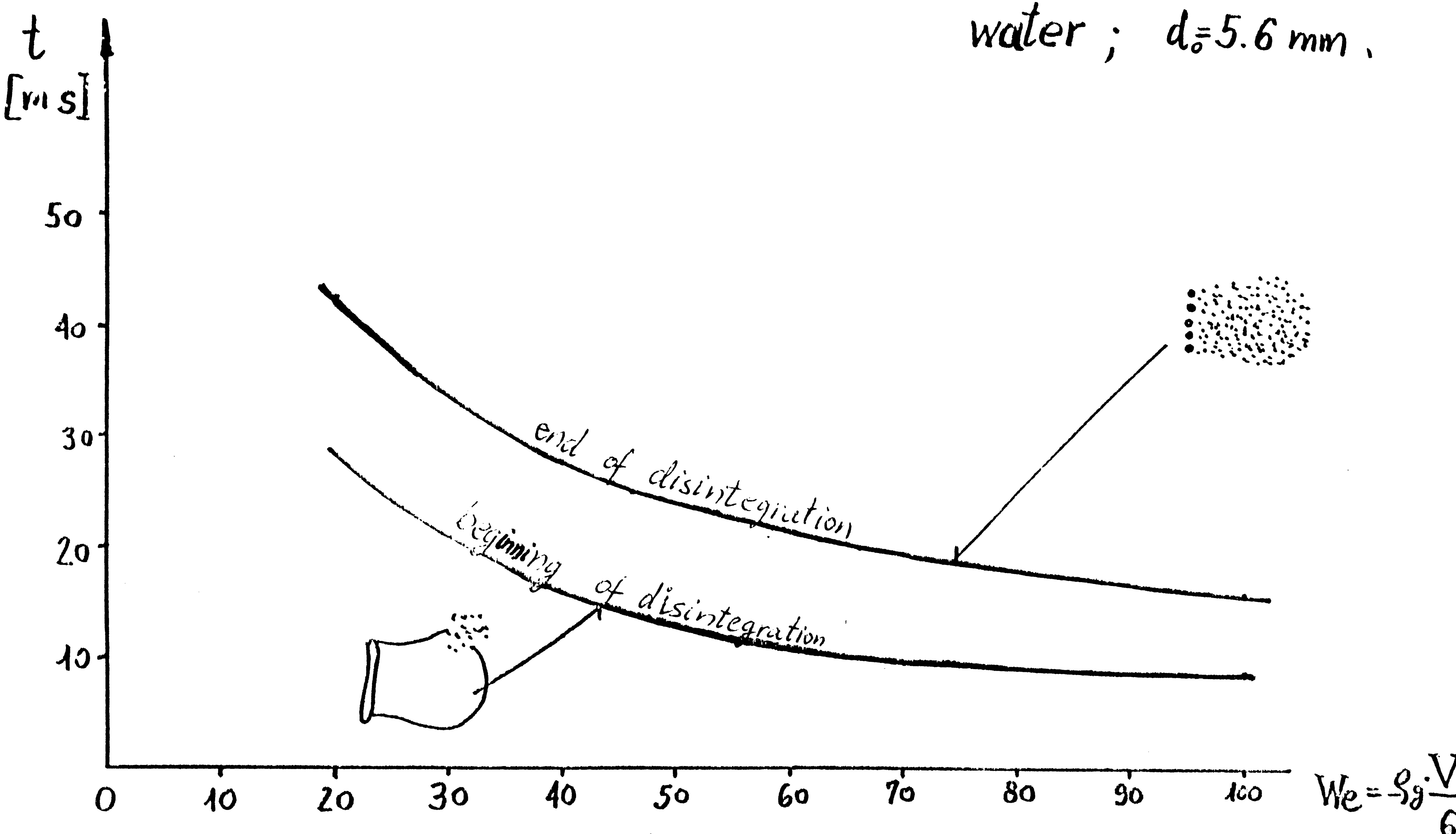

water ; $d_o = 5.6$ mm.
t [ms]
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
end of disintegration
beginning of disintegration
We = ϱg·V

Fig. 4.

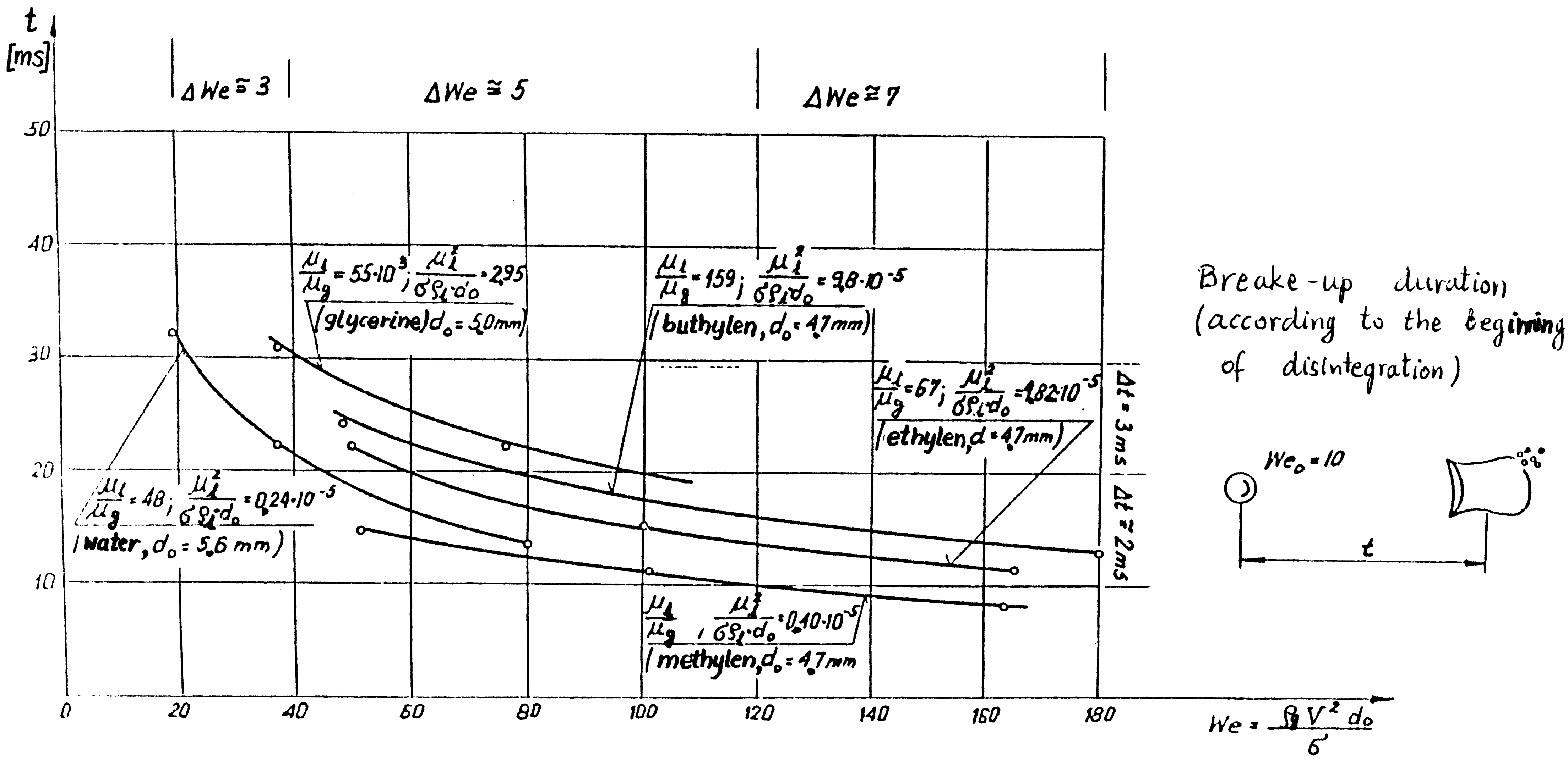
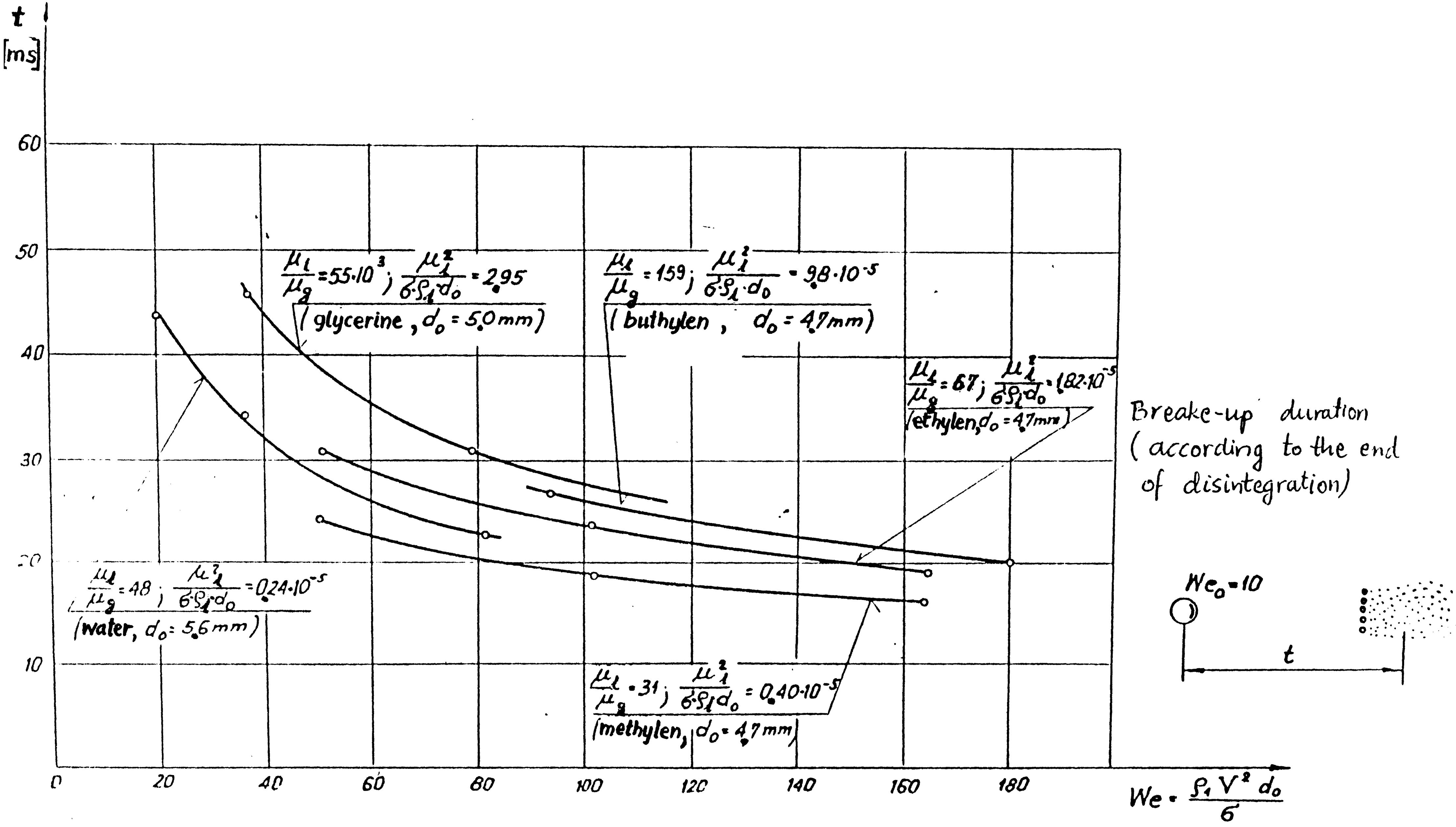

t [ms]
ΔWe ≅ 3
ΔWe ≅ 5
ΔWe ≅ 7
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
$\frac{\mu_l}{\mu_g} = 55\cdot10^3; \frac{\mu_l^2}{\sigma\rho_l d_o} = 2.95$
(glycerine) $d_o = 5.0$ mm
$\frac{\mu_l}{\mu_g} = 159; \frac{\mu_l^2}{\sigma\rho_l d_o} = 9.8\cdot10^{-5}$
(buthylen, $d_o = 4.7$ mm)
$\frac{\mu_l}{\mu_g} = 67; \frac{\mu_l^2}{\sigma\rho_l d_o} = 1.82\cdot10^{-5}$
(ethylen, $d = 4.7$ mm)
$\frac{\mu_l}{\mu_g} = 48; \frac{\mu_l^2}{\sigma\rho_l d_o} = 0.24\cdot10^{-5}$
(water, $d_o = 5.6$ mm)
$\frac{\mu_l}{\mu_g}, \frac{\mu_l^2}{\sigma\rho_l d_o} = 0.40\cdot10^{-5}$
(methylen, $d_o = 4.7$ mm
Δt = 3ms
Δt ≅ 2ms
Breake-up duration
(according to the beginning
of disintegration)
$We_o = 10$
t
$We = \frac{\rho_g V^2 d_o}{\sigma}$

Fig. 5.

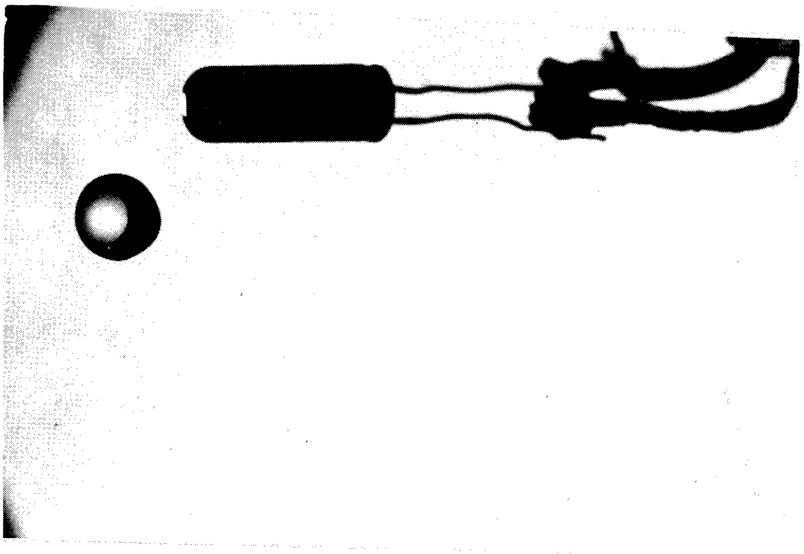


t [ms]
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
$\frac{\mu_l}{\mu_g}=55\cdot10^3$; $\frac{\mu_l^2}{\sigma\cdot\rho_l\cdot d_o}=2.95$
(glycerine, $d_o=5.0$ mm)
$\frac{\mu_l}{\mu_g}=159$; $\frac{\mu_l^2}{\sigma\cdot\rho_l\cdot d_o}=9.8\cdot10^{-5}$
(buthylen, $d_o=4.7$ mm)
$\frac{\mu_l}{\mu_g}=67$; $\frac{\mu_l^2}{\sigma\cdot\rho_l d_o}=1.82\cdot10^{-5}$
(ethylen, $d_o=4.7$ mm)
$\frac{\mu_l}{\mu_g}=48$; $\frac{\mu_l^2}{\sigma\cdot\rho_l\cdot d_o}=0.24\cdot10^{-5}$
(water, $d_o=5.6$ mm)
$\frac{\mu_l}{\mu_g}=31$; $\frac{\mu_l^2}{\sigma\cdot\rho_l d_o}=0.40\cdot10^{-5}$
(methylen, $d_o=4.7$ mm)
Breake-up duration (according to the end of disintegration)
$We_o=10$
t
$We=\frac{\rho_1 V^2 d_o}{\sigma}$

Fig. 6.

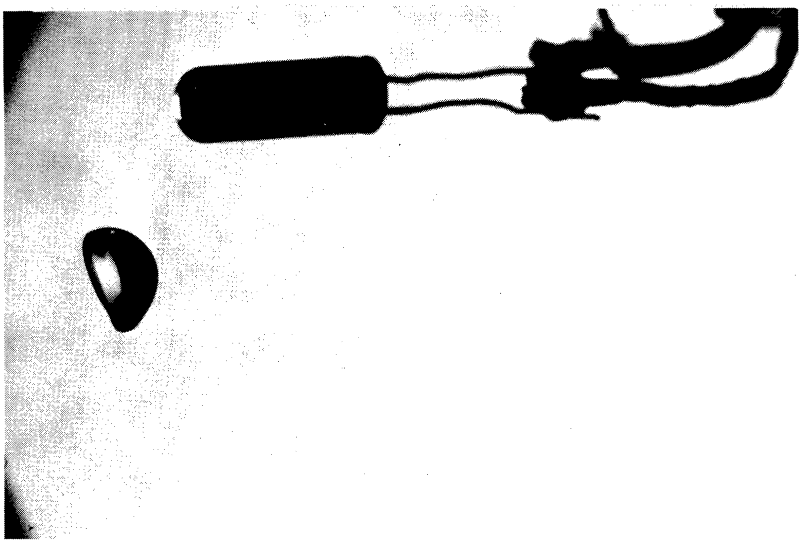
ir

ow



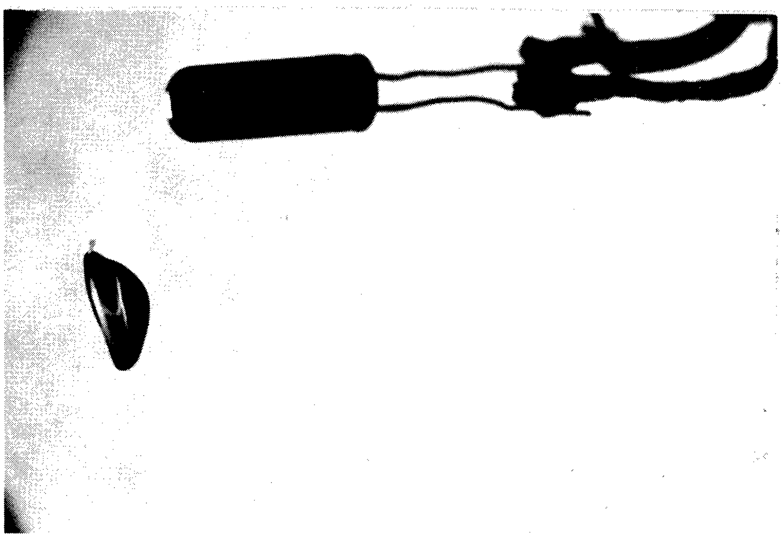
t=0

t=0



t=13.18 ms

t=13.18 ms

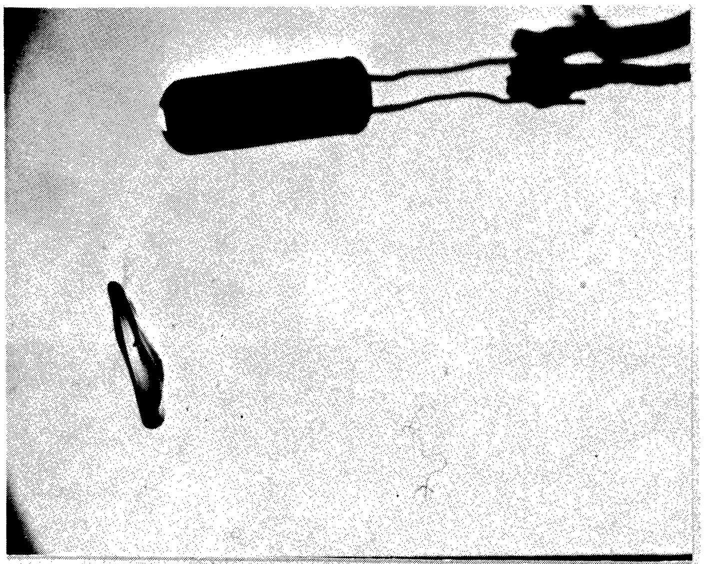


t=15.45 ms

t=15.45 ms

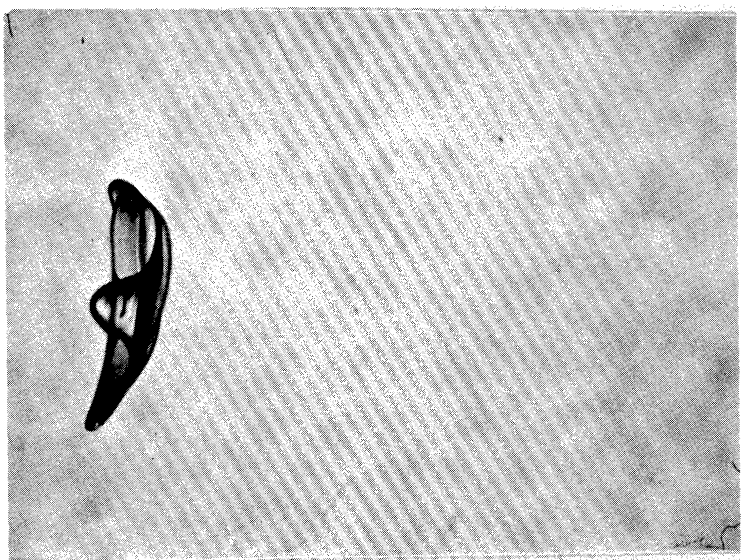
Fig II - 1

air
flow



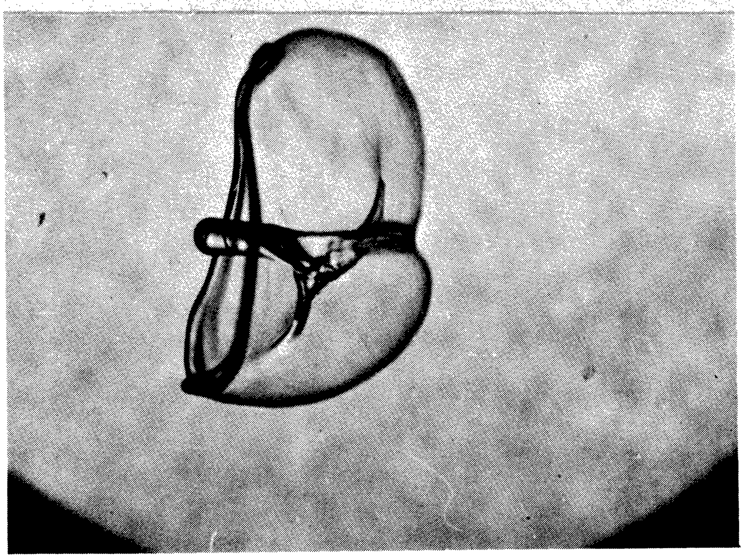
t=18.02 ms

t=18.02ms



t=27.71ms

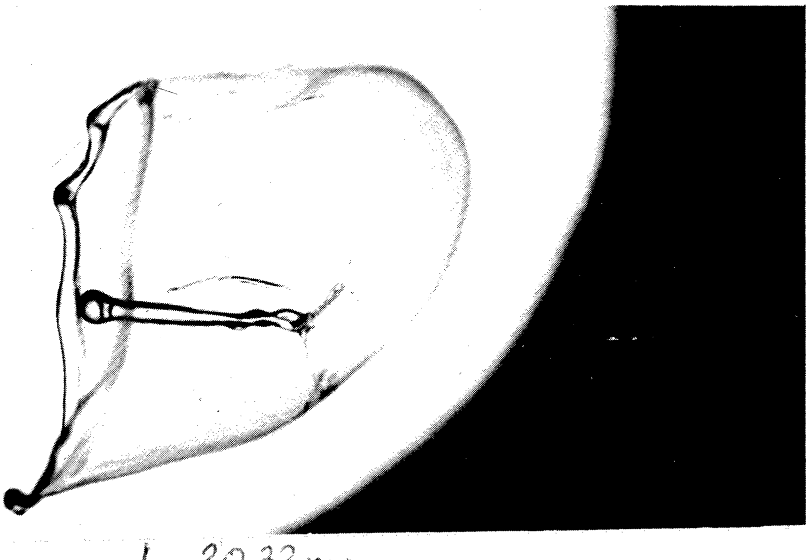
t=29.71ms



t=30.00ms

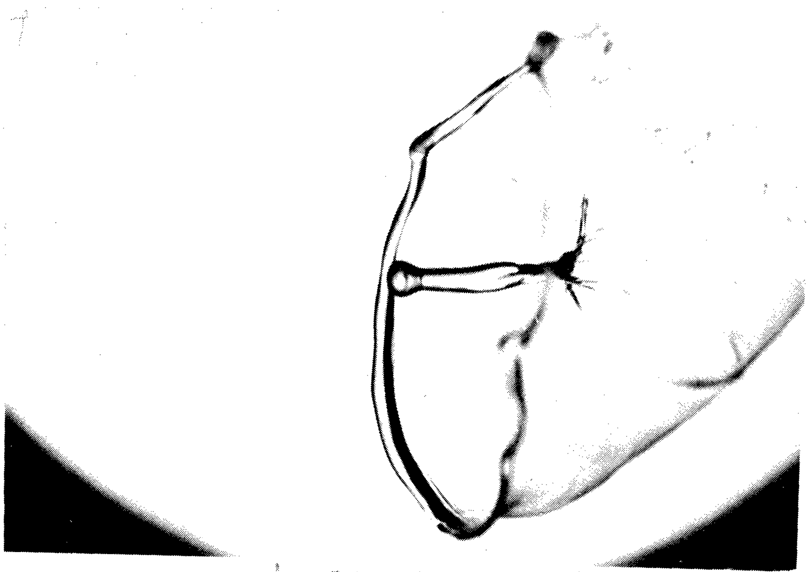
Fig II - 2

air
flow



t = 30.32 ms

t=30.32ms



t = 32.44 ms

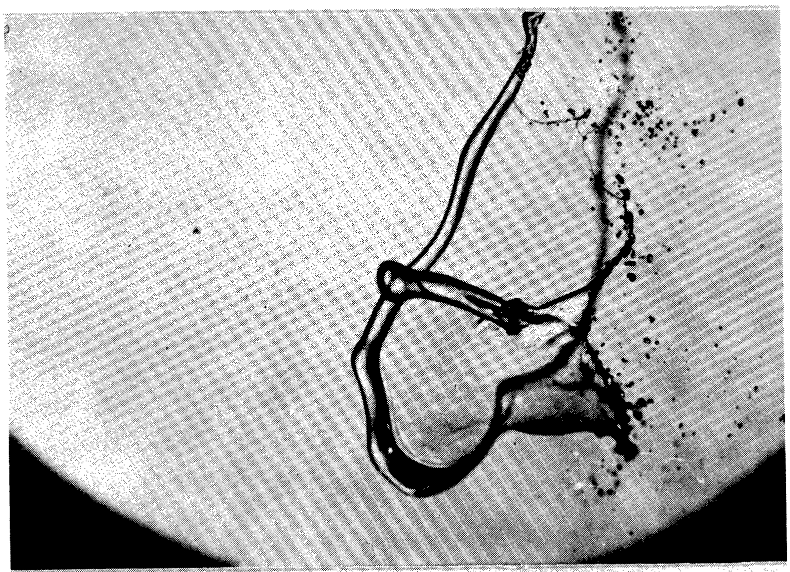
t = 32.44ms

t=32.67ms

t = 32.67ms

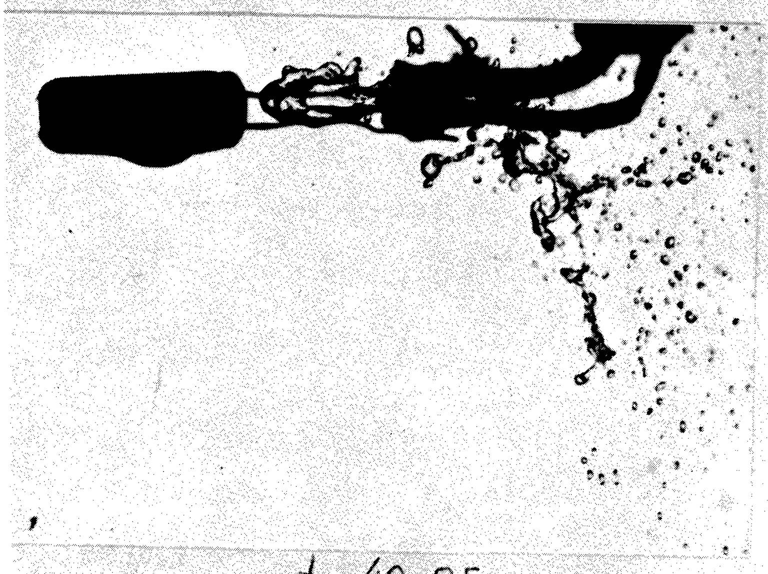
Fig 7-3

Air flow



t = 36.11 ms

t = 36.11ms



t = 40.85 ms

t = 40.85ms

Fig 3-4