

MEASUREMENT OF LIQUID DROPLET DISINTEGRATION MECHANISMS

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Abstract—An experimental study is made of deformation mechanisms and break-up duration of liquid droplets due to an air stream. A relationship between flow conditions and the type of droplet deformation mechanisms has been obtained as well as some data concerning duration of disintegration. The investigations have been carried out for several liquids of various viscosity.

INTRODUCTION

The problem which is herewith presented concerns the mechanisms and the kinematics of deformation and disintegration of liquid 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 by many authors (e.g. Volynskii 1948, Lane 1951, Hinze 1955, Dodd 1964, Hanson *et al.* 1964 among others). Thus, it is well known. However, the author's interest was to investigate the behaviour of liquid droplets before and during a break-up, as well as the break-up duration. Several authors have suggested many different semi-theoretical formulae for estimation of the break-up duration (e.g. Littaye 1943; Engel 1958; Levich 1962). Because the formulae were rather approximate, experimental investigation seemed to be worth considering. The first experimental data concerning water droplets disintegrated in a steam tunnel were published by Hassler (1972). Simpkins (1971) investigated development of drops deforming in air shock tube. He studied the growth rate of droplets as a function of time and flow conditions.

The paper presented herewith includes some results of experimental study of several other liquids such as methanol, ethanol, butanol and glycerine. The range of liquid viscosity changes over 10^3 times.

Dimensionless analysis of the conservation equations of gas flow and liquid flow, which was made considering the boundary conditions [1]–[3], gives several dimensionless parameters. The boundary conditions:

$$(p_G)_b + \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) = (p_L)_b \quad [1]$$

$$(\tau_G)_b = (\tau_L)_b \quad [2]$$

$$(V_G)_b = (V_L)_b \quad [3]$$

where p_G is the pressure of gas; p_L is the pressure of liquid; τ_G is the shear stress of gas; τ_L is the shear stress of liquid; V_G is the velocity of gas; V_L is the velocity of liquid; σ is the surface tension; and r_1 and r_2 are radii of droplet curvature. Subscript b means boundary conditions between gas and liquid.

The analysis has been done by many authors for different systems. For example: gas-liquid films or gas-droplets were studied by Kutateladze & Stirikovich (1958), liquid jets coming out from nozzles and injectors, by Orzechowski (1976), and liquid droplets in a gas stream by Hinze (1955) and Krzeczowski (1969, 1972).

The dimensionless parameters, obtained from the last of the above mentioned investigations are presented below. The analyses have been done for incompressible, steady flow, neglecting the gravity forces and heat transfer. As a result the following parameters were obtained:

$$\text{Str} = \frac{V \cdot t}{d}, \quad [4]$$

$$\text{We} = \frac{\rho_G V^2 d}{\sigma}, \quad [5]$$

$$\text{La} = \frac{\rho_L \sigma d}{\mu_L^2}, \quad [6]$$

$$\frac{\mu_L}{\mu_G}, \quad \frac{\rho_L}{\rho_G}, \quad \frac{V_L}{V_G}, \quad [7], [8], [9]$$

where Str is the Strouhal Number; We is the Weber Number; La is the Laplace Number; ρ_G is the gas density; ρ_L is the liquid density; μ_G is the gas viscosity; μ_L is the liquid viscosity; d is the droplet diameter; t is the time; and $V = |V_G - V_L|$.

For a droplet drifting freely in a flow, the velocity ratio [9] is unnecessary (the group [9] is important at disintegration processes by injectors).

In the experiment presented in this paper the ratio of density [8] was almost constant and did not influence the results. It has been neglected. Therefore, three parameters ([5]–[7]) are assumed to be important to the process:

$$\text{Str} = f\left(\text{We}, \text{La}, \frac{\mu_L}{\mu_G}\right). \quad [10]$$

EXPERIMENTAL FACILITY AND APPARATUS

The facility is shown in the sketch (figure 1). A wind tunnel and droplet generator were used. Liquid particles dropping gravitationally 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. Liquid droplets crossed the boundary layer at a velocity of 2.1–2.2 m/s. Therefore the total entering time was 1.7–3 ms (depending on the droplet diameter) and usually did not exceed 8–10 per cent of the total droplet break-up duration (the maximum value was 17 per cent).

The droplet temperature was measured with a micro thermocouple located inside the droplet generator capillary, just at its inlet. Obviously, after the droplet had been torn off its temperature could not be measured any longer. The measured droplet temperature was used to derive values of dynamic viscosity and surface tension.

The temperature drop of liquid due to evaporation was computed for liquid particles falling down from capillary to the air stream. The maximum values of the temperature drop and relative errors of dynamic viscosity and surface tension are shown for some liquids in the Appendix.

The mechanism of droplet deformation and disintegration was investigated by means of photo camera and a spark flash. The flash duration ($\sim 1 \mu\text{s}$) proved suitable for the purpose. The droplet deformation measurement was simple. Droplets entrained in the air stream cut the laser beam. The signal passed through the photo-cell, indicating the beginning of the process, and caused the spark-flash to fire after a precept delay of time. By changing time delay from drop to drop, several pictures for different stages of droplet break-up were taken. The moment at which the Weber Number become equal to 10 for the centre of droplet was considered the initial moment of the process. The conditions of the experiment are shown in table 1.

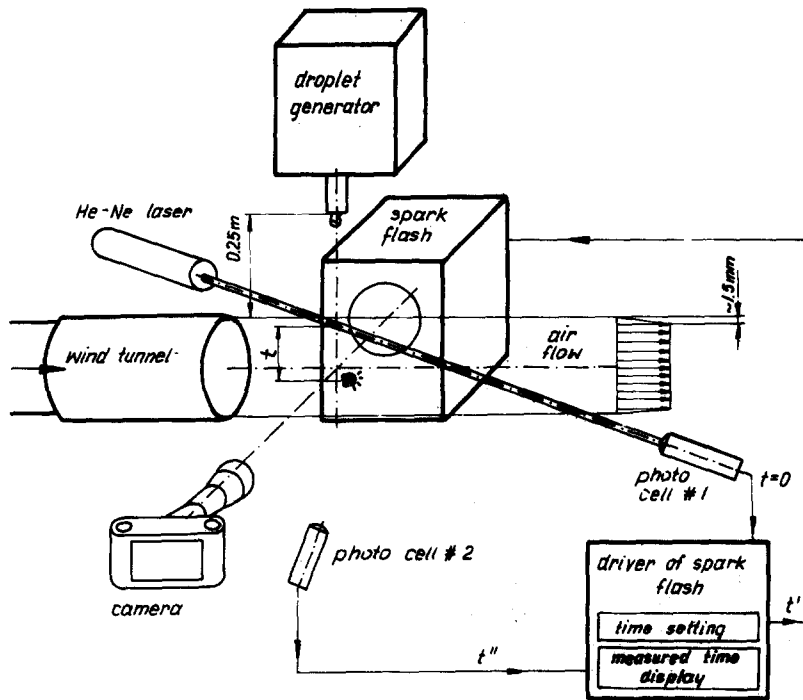


Figure 1. Experimental facility; flow direction left to right.

Table 1. The conditions of the experiments

liquid		methanol	water	ethanol	butanol	water-glyc- erine solution (50 percent)	glycerine
flow data		CH ₃ OH	H ₂ O	C ₂ H ₅ OH	C ₄ H ₉ OH		C ₃ H ₈ O ₃
μ_L	$\frac{kg}{m \cdot s}$	$0.578 \cdot 10^{-3}$	$0.892 \cdot 10^{-3}$	$1.243 \cdot 10^{-3}$	$2.950 \cdot 10^{-3}$	0.170	1.020
ρ_L	$\frac{kg}{m^3}$	$0.792 \cdot 10^3$	$1.002 \cdot 10^3$	$0.796 \cdot 10^3$	$0.870 \cdot 10^3$	1.167	$1.234 \cdot 10^3$
σ	$\frac{kg}{s^2}$	$22.6 \cdot 10^{-3}$	$72 \cdot 10^{-3}$	$22.8 \cdot 10^{-3}$	$24.6 \cdot 10^{-3}$	$59.4 \cdot 10^{-3}$	$57.11 \cdot 10^{-3}$
d	mm	4.7 ; 2.1	5.6 ; 3.1 ; 2.9	4.7 ; 2.1	4.7 ; 2.2	5.0	5.0
$\frac{l}{La}$	-	0.40 $0.89 \cdot 10^{-5}$	$(0.24+0.51) \cdot 10^{-5}$	$1.82 \cdot 10^{-5}$	$9.8 \cdot 10^{-5}$ 21.0	0.004	2.95
$\frac{\mu_L}{\mu_0}$	-	31	47.9	66.8	158.7	$9.15 \cdot 10^3$	$54.9 \cdot 10^3$
V	$\frac{m}{s}$	14.1 - 30.9				17.2 ÷ 32	18.1 ÷ 32.0
$P = \frac{\rho_0 V^2}{2}$	$\frac{N}{m^2}$	125 - 590				195 ÷ 645	205 ÷ 645
$We = \frac{\rho_L V^2 d}{\sigma}$	-	29.0 + 103.0	13.5 + 80.5	22.8 + 102.0	22.5 + 180	31.3 + 109	98.0 + 113.1

RESULTS OF THE EXPERIMENTS

The interest of the investigation was focused upon the following problems: (i) classification of types of droplet deformation; (ii) kinematics of deformation; and (iii) duration of disintegration. Some selected results are presented below.

(i) Figures 2-5 show photographically four types of droplet distortion (the pictures have been taken at the increasing Weber Number).

There are four typical cases of liquid droplet break-up (listed also with increasing We Number):

- (1) Bag mechanism (figure 2).
- (2) Bag-jet mechanism (figure 3).
- (3) Transition mechanism (figure 4).
- (4) Shear (or stripping off) mechanism (figure 5).

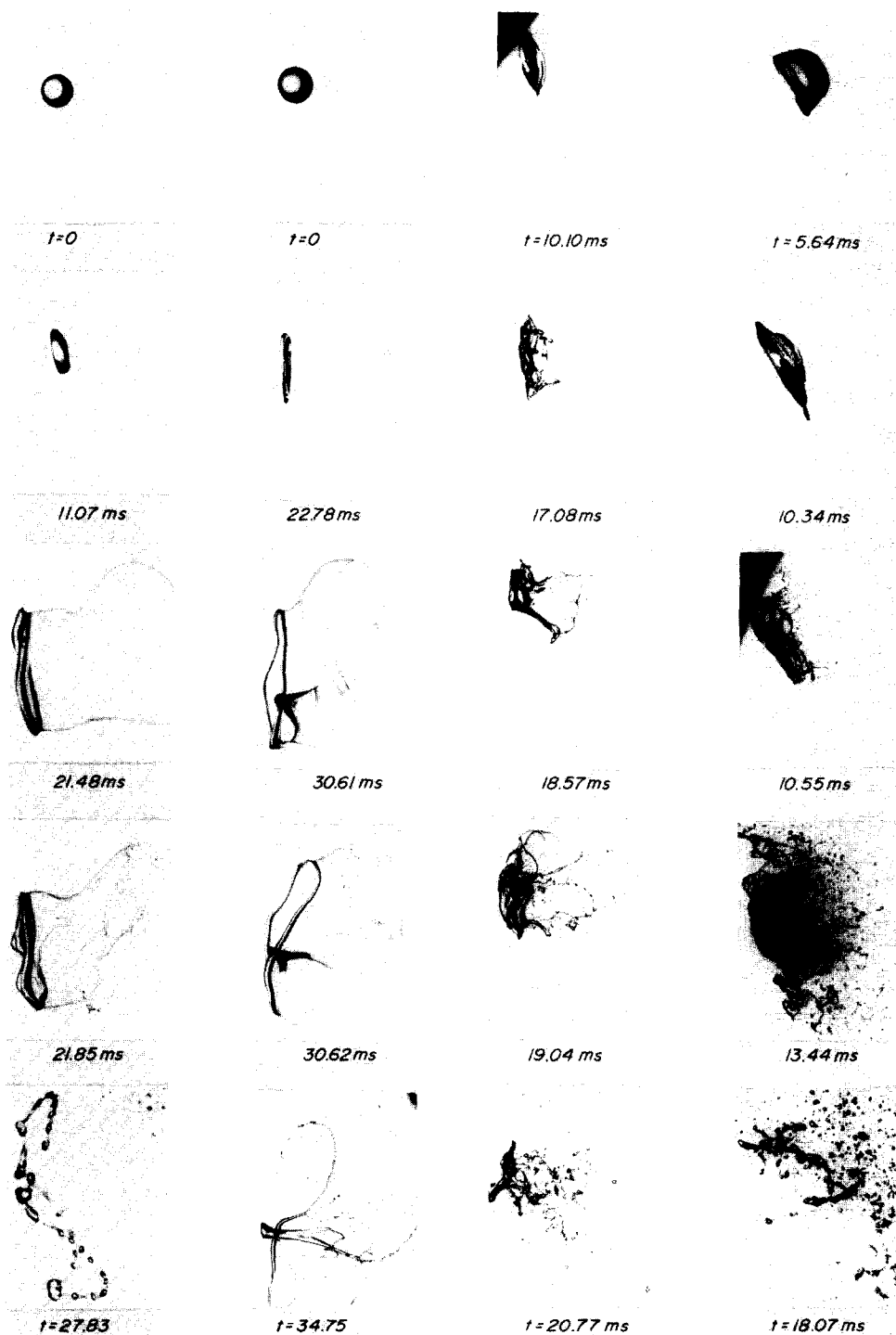


Figure 2. Some typical pictures of bag mechanism of droplet break-up; flow direction left to right. Water droplets, $d_0 = 3.1$ mm, $We = 13.5$, $(1/La) = 0.43 \cdot 10^{-5}$.

Figure 3. Some typical pictures of bag-jet mechanism of droplet break-up; flow direction left to right. Glycerine droplets, $d_0 = 5.0$ mm, $We = 36.0$, $(1/La) = 2.95$.

Figure 4. Some typical pictures of transition mechanism of droplet break-up; flow direction left to right. Butanol droplets, $d_0 = 4.7$ mm, $We = 48.1$, $(1/La) = 9.8 \cdot 10^{-5}$.

Figure 5. Some typical pictures of shear (stripping off) mechanism of droplet break-up; flow direction left to right. Ethanol droplets, $d = 4.7$ mm, $We = 162$, $(1/La) = 1.82 \cdot 10^{-5}$.

One may notice that with increasing We number the nature of disintegration changes towards a more chaotic mechanism. This is due to the fact, that the pressure acting on the droplet surface changes from a uniform distribution at a low Weber number to a nonuniform and unsteady one at a high Weber Number.

All kinds of droplet deformation start from basic shape, so called "liquid disc" (see figure 6). Thereafter the velocity of deformation increases rapidly. Thus, according to the conditions of the flow, the disc may become a hollow sphere (bag—case 1, figure 2) or a hollow sphere with a jet (case 2, figure 3) before disintegration. Cases 3 (figure 4) and 4 (figure 5) exhibit more irregular or "bulgy" deformation. For case 3 the break-up is also more chaotic than for cases 1 and 2, while for case 4 the break-up is more or less continuous. It is symptomatic to the transition mechanism (case 3, figure 4) that there are both bubbles and filaments during disintegration. The shear mechanism (case 4, figure 5) is characterised by filaments alone.

The transition from the first type of droplet break-up to the second one with changing We number is distinct. However, the transition between other types mentioned above ($2 \leftrightarrow 3$ and $3 \leftrightarrow 4$) are gradual.

In order to formulate a relationship between the conditions of the flow and the deformation mechanism a transition map has been established† (figure 7). The diagram is based mainly on experimental data of the author's investigations but others authors' data (Hanson *et al.* 1964, Hassler 1972, Hinze 1955, Lane 1951) are included. The typical cases described above are indicated on the graph which is divided into corresponding regions. This provides information, necessary to predict liquid droplet behaviour in a gas stream.

(ii) The kinematics of the four kinds of deformation for the selected cases concerning water droplets are shown on the graphs (figures 8–11) in order to describe the process more quantitatively. The rate of deformation has been defined by the ratio of dimensions (d/d_0) and (h/d_0) (where h is the longitudinal one and d_0 is the initial diameter of a droplet). The nature of deformation kinetics is similar for the bag and bag-jet mechanisms (figures 8 and 9). Also the transition mechanism and the shear mechanism (figures 10 and 11) are similar. The Stouhal number, concerning the rapid rise of the ratio (h/d_0), decreases with the Weber number.

(iii) Droplet break-up time was studied for several conditions (table 1). Break-up time of large water droplets has been presented as a function of the Weber number in figure 12. While the lower curve shows the beginning of disintegration, the upper one concerns the end. Similar results which have been obtained for other liquids are shown in figures 13 and 14, and figures 15 and 16. Figures 13 and 15 refer to the beginning of disintegration, while figures 14 and 16 refer to

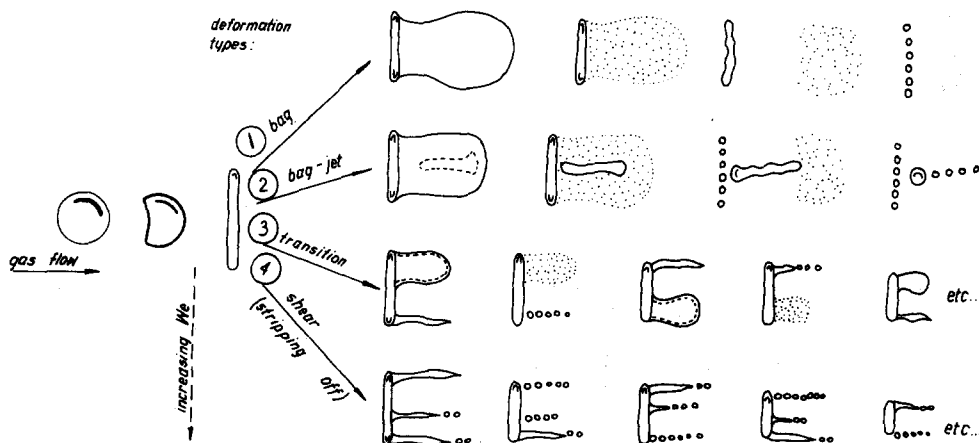


Figure 6. Sketch of droplet deformation development.

†This has been done assuming three dimensionless parameters important to the process: We , La , (μ_L/μ_G).

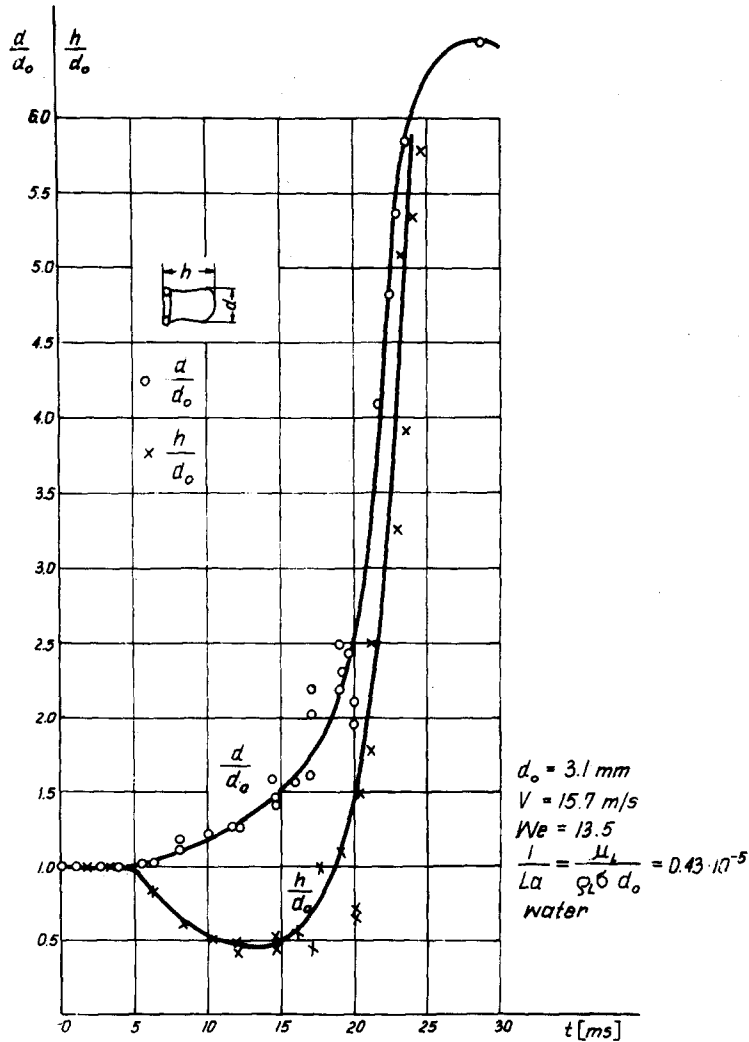


Figure 8. Kinematics of droplet deformation of bag mechanism (see figure 2).

the end of the process.† The curves are qualitatively similar, but there is a significant quantitative difference. Some results of the experiment have been compared with the formulae mentioned in the Introduction (see table 2). It appears that Engel's formula fits the presented experiment better than other formulae.

CONCLUSIONS

The mechanism of droplet deformation and disintegration as well as break-up duration depend on the Weber number, Laplace number and the ratio (μ_L/μ_G). The influence of the Weber number is the strongest.

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

†The data points concern mean break-up time, obtained from five tests. Mean scatter of results did not exceed 1.5 ms.

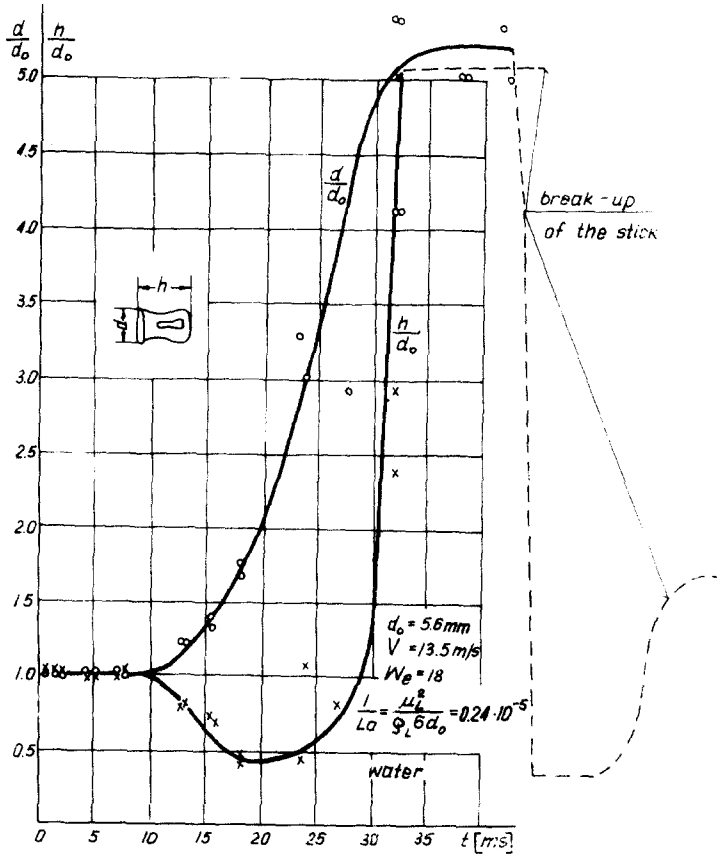


Figure 9. Kinematics of droplet deformation of bag-jet mechanism (see figure 3).

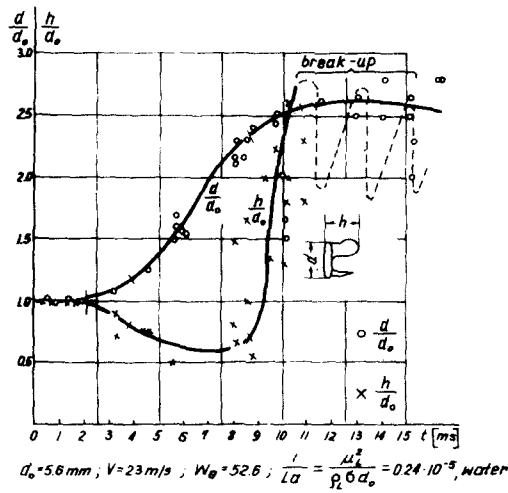


Figure 10. Kinematics of droplet deformation of transition mechanism (see figure 4).

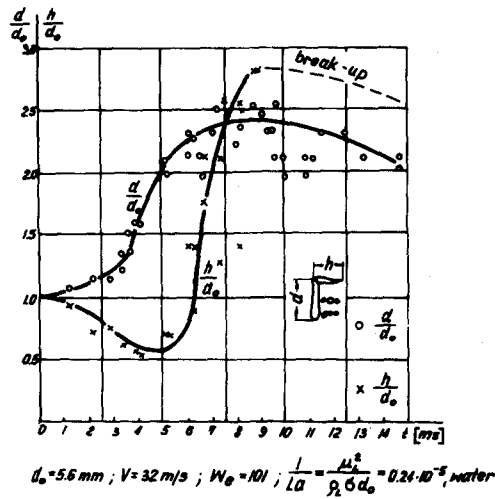


Figure 11. Kinematics of droplet deformation of shear (stripping off) mechanism (see figure 5).

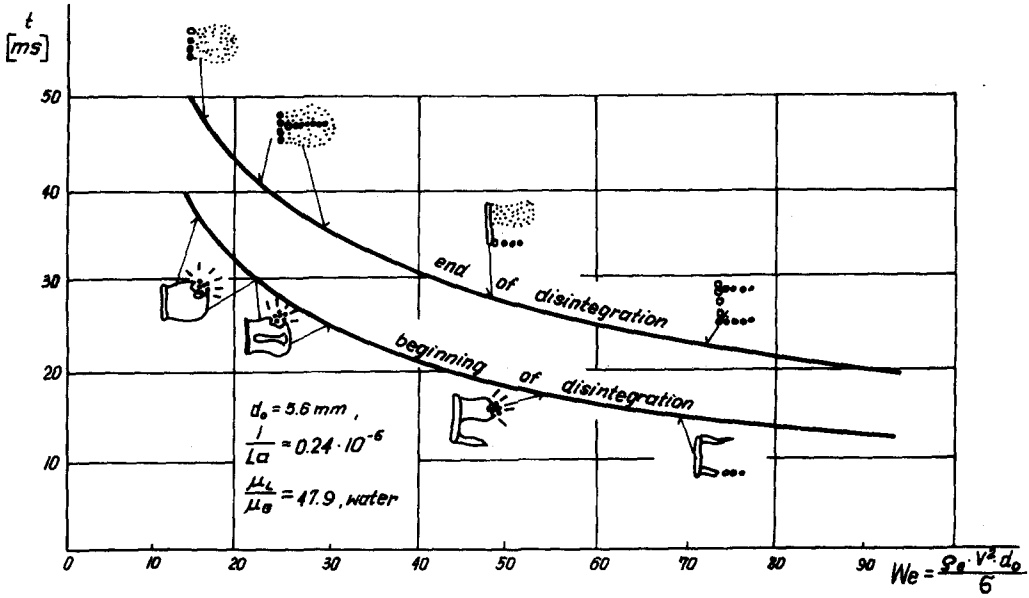


Figure 12. Break-up duration vs the Weber Number for water droplets (beginning and the end of disintegration).

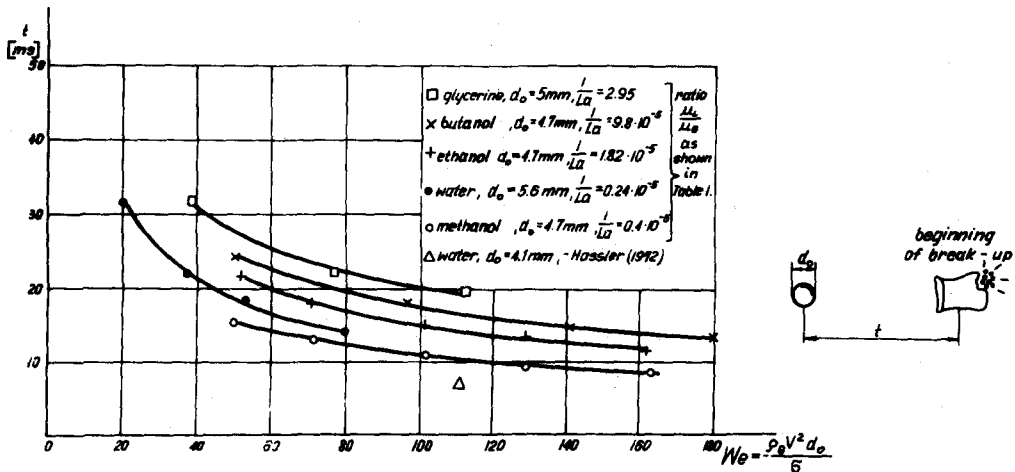


Figure 13. Break-up duration vs the Weber Number for several liquids—beginning of disintegration (series of large droplets).

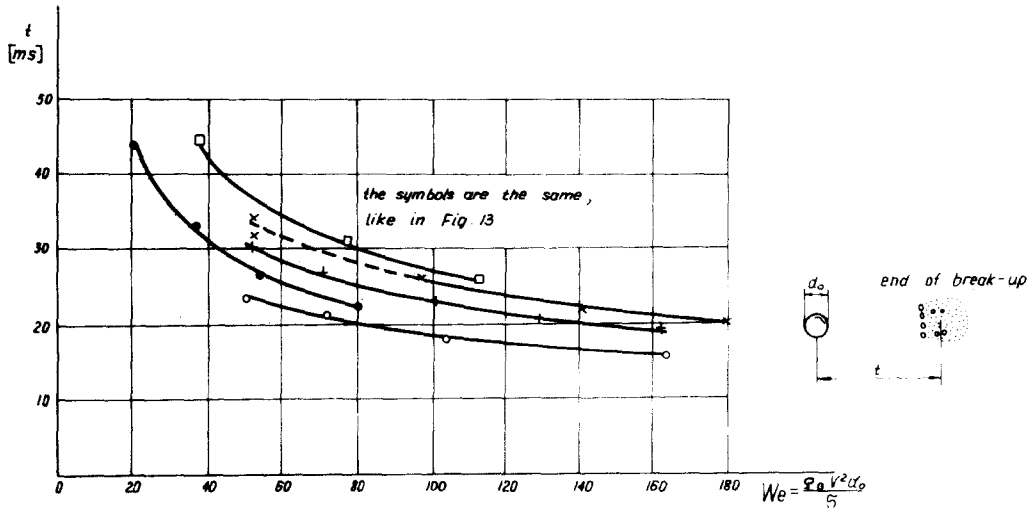


Figure 14. Break-up duration vs the Weber Number for several liquids—end of disintegration (series of large droplets).

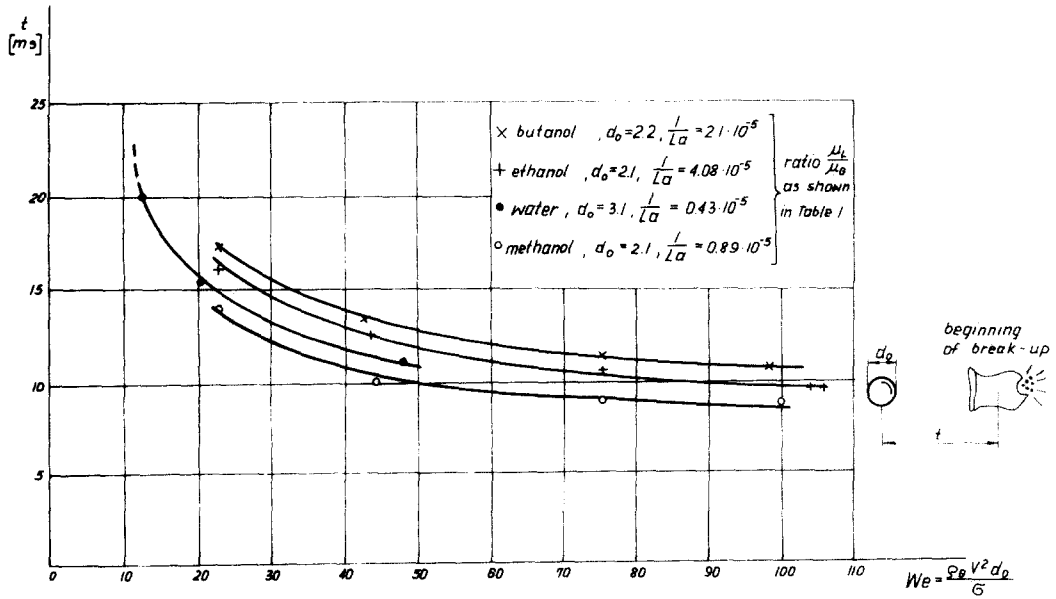


Figure 15. Break-up duration vs the Weber Number for several liquids—beginning of disintegration (series of small droplets).

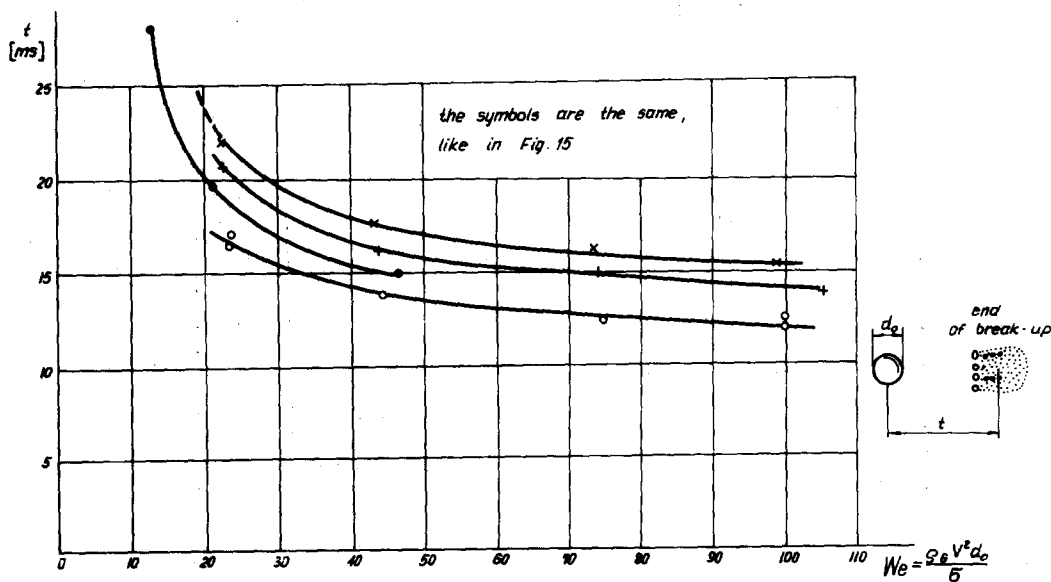


Figure 16. Break-up duration vs the Weber Number for several liquids—end of disintegration (series of small droplets).

Table 2. Droplet break-up duration (in milliseconds) according to some formulae compared with the experiment

flow conditions Authors and formulae	methanol				water				glycerine	
	d = 2.1 mm		d = 4.7 mm		d = 3.1 mm		d = 5.6 mm		d = 5.0 mm	
	We = 23	We = 100.1	We = 51.2	We = 183	We = 13.5	We = 47.5	We = 19.6	We = 80.5	We = 36	We = 113.1
Litvayev (1943) $t = \frac{\pi}{4} \sqrt{\frac{\rho_e d^3}{6}}$	14.2	14.2	46.4	46.4	15.9	15.9	38.6	38.6	58.8	56.8
Engel (1958) $t = 2.8 \frac{d}{V} \sqrt{\frac{\rho_e}{\rho_e}}$	10.5	5.04	23.6	13.3	15.8	8.29	31.5	15.6	24.4	13.8
Levich (1962) $t \sim \frac{\mu_e d}{6}$	0.054	0.054	0.12	0.12	0.0038	0.038	0.07	0.07	89.2	89.2
the results of the experiment	17.1	12.3	23.8	18.2	29.1	15.0	44.4	23.0	45.5	28.7

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APPENDIX

The temperature drop due to evaporation was estimated by means of a relationship of Hsu *et al.* (1954):

$$\text{Sh} = 2(1 + 0.272 \text{Re}^{0.5} \text{Sc}^{0.33})$$

where $\text{Sh} = (h_D \cdot d/D)$ is the Sherwood Number; $\text{Sc} = (\gamma_G/D)$ is the Scott Number; h_D is the mass transfer coefficient; and D is the diffusion coefficient. This formula is similar to those of other authors, mentioned and discussed by Kwan Lee & Ryley (1968).

The estimation has been done assuming that evaporation process takes energy from the conduction boundary layer of thickness equal to the penetration depth expressed by the formula, proposed among others by Beek & Muttzall (1975):

$$l_p = \sqrt{\left(\pi \frac{\lambda_L \cdot t}{C_{pL} \cdot \rho_L} \right)},$$

where l_p is the penetration depth, λ_L is the thermal conductivity of liquid, C_{pL} is the specific heat of liquid, t is the time (in this case, time t is equal to the time of droplet downfall).

The computation was carried on taking into account two phases of droplet evaporation:

First—which takes place at droplet tearing off process of duration of ~ 0.5 s ($V = 0$).

Second—at droplet gravitational downfall of duration of ~ 0.24 s.

The maximum values of the temperature drop ΔT and the relative error of surface tension ($\Delta\sigma/\sigma$) are shown in the table below. Error of dynamic viscosity is also included. It has been estimated according to the mean temperature of liquid particle because the deformation processes take place in the whole mass of droplet.

	Methanol d = 2.1 mm	Water d = 2.7 mm	Ethanol d = 2.1 mm
ΔT °C	8.4°C	0.8°C	6.4°C
$\frac{\Delta\sigma}{\sigma}$ per cent	3.4	0.16	2.3
$\frac{\Delta\mu_L}{\mu_L}$ per cent	5.2	1.2	4.1
The mean value for the whole mass of droplet.			

ΔT is the temperature of droplet conduction boundary layer.