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ATOMIZATION OF A LIQUID BY A ROTATING DISC AND "SECONDARY" BREAK-UP OF DROPLETS

V. F. Dunskii and N. V. Nikitin

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Atomization of a liquid by a rotating disc is investigated. In spite of the high values of the Weber number (up to 13.0), atomization takes place without "secondary" break-up of the droplets.

Disc atomizers are widely used in industry, agriculture and in laboratories. It has been established [1-6] that when a liquid is fed in the form of a continuous jet at a small flow rate to the center of a rotating disc, approximately identical "basic" droplets are formed of diameter

$$d = \frac{C}{\omega}\left(\frac{\sigma}{D\rho_l}\right)^{1/2}, \tag{1}$$

together with finer "secondary" droplets. Equation (1) expresses the fact that there is a constant ratio between the pressure of centrifugal forces and capillary pressure for a hemisphere of liquid at the rim of the rotating disc. The relative number of secondary droplets has been evaluated differently by various investigators. The discrepancies are probably attributable to inadequate experimental techniques. In our tests we tried to avoid these shortcomings as this matter is one of primary importance in connection with the use of the disc atomizer as a laboratory generator of monodisperse fog.

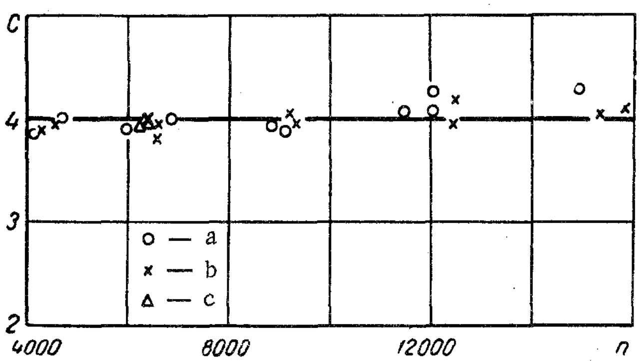

Fig. 1. Values of the constant C for various values of n: a, b) Flow rate 0.1 and 0.03 cm^3/sec (transformer oil); c) flow rate 0.03 (diesel fuel).

The experimental setup was as follows. A continuous jet of liquid was injected from the needle of a syringe into the center of a cylindrical recess in a horizontal disc rotated by an electric motor. The disc was of duralumin and was 7.0 cm in diameter. Its working surface was lapped until no lines were visible to the eye. A horizontal sheet of paper was located 9 cm below the plane of the disc. Regular shaped rings were formed on the paper by deposited basic droplets of colored liquid (transformer oil, $\rho_l = 0.892$ g/cm^3, $\nu_l = 0.218$ cm^2/sec, $\sigma = 33.2$ g/sec^2, and diesel fuel, $\rho_l = 0.832$ g/cm^3, $\nu_l = 0.0278$ cm^2/sec, $\sigma = 30.6$ g/sec^2). The secondary droplets were deposited mainly within the ring. Evaporation proceeded so slowly that its effect may be neglected.

To determine the relative weight of the deposited droplets, we measured the increase of weight of the paper ring on which the circular mark was formed. From the results of weighing and by measuring the total quantity of liquid used, we determined the relative weight of the basic droplets.

This method allowed the determination of the relative weight of the basic droplets, and hence the secondary droplets, without interfering with the deposition process.

Besides weighing the ring, we determined the inner and outer radii of the circular trace and measured the deposited droplets by means of a microscope. A microscope slide, covered with a Petri glass, was positioned to enclose the specimen of basic droplets on the sheet of paper within the circular trace. The slide was uncovered for 1-2 sec during a test; in each exposure the deposited droplets occupied less than 1% of the area of the slide, and the probability of their merging was slight. Before the test the slide was covered with a thin layer of silicone to achieve a constant contact angle of droplets of different sizes [7]. The experimentally determined mean value of the droplet spreading coefficient proved to be 1.93.

Tests were conducted with liquid flow rates of 0.03 and 0.10 cm^3/sec and disc rotation rates from 4000 to 16 000 rpm. The results are shown in Fig. 1. The data obtained confirm the validity of (1); the value of C remains approximately constant (3.73-4.28, arithmetic mean 4.0, root mean square deviation 3.5%). The root mean square deviation for d varied from 1.7 to 6.7%. These values are probably greater than the actual ones, since they reflect not only the actual differences in droplet dimensions, but also inaccuracies of measurement, nonuniformity of droplet spreading on the silicone layer, etc.

The results of weighing indicated that, for the small flow rate (0.03 cm^3/sec) ε = 75-80%, i.e., 20-25% of the liquid occurs in the secondary droplet portion; the value of ε decreases with increase of flow rate. Therefore, the small secondary droplets compose a considerable fraction of the atomized liquid and the main fraction of the total number of droplets. Consequently, successful use of a disc atomizer as a generator of monodisperse aerosols is practically impossible without separation of the secondary droplets, by inertia or gravity, for example.

As regards gravitational separation of droplets, the question arises as to what is the trajectory of the basic droplets, and if the values are independent.

We shall calculate the "ballistic" trajectory of a solid sphere of diameter d, moving under its inertia through still air, with an initial velocity equal to the peripheral speed of the disc and tangential to its rim. The drag force of the air and the force of gravity act on the sphere. The sphere motion is described by the equations:

$$m\frac{du}{d\tau} = -F_x, \tag{2}$$

$$m\frac{dw}{d\tau} = mg - F_z. \tag{3}$$

The origin of the coordinates is located on the rim of the disc, the x axis is tangential to the rim, and the z axis is downwards. The rate of fall under gravity, ω, of spheres of sizes of interest to us is determined by Stokes law. To determine the horizontal component of the air resistance we use the Klyachko's empirical formula [8], according to which the resistance coefficient for a sphere in the range 3 < Re < 400 will be

$$\psi = \frac{24}{\mathrm{Re}} + \frac{4}{\sqrt[3]{\mathrm{Re}}} \ . \tag{4}$$

By integration of (2) and (3), taking into account Stokes' law, the Klyachko formula and the initial conditions, we obtain for the three unknowns τ, x, z the set of three equations:

$$\tau = a \ln \frac{u_0}{u}\left(\frac{1 + bu^{2/3}}{1 + bu_0^{2/3}}\right)^{3/2}, \tag{5}$$

$$x = \frac{3a}{b}\left[u_0^{1/3} - u^{1/3} - \frac{1}{\sqrt{b}}\left(\operatorname{arc\,tg} u_0^{1/3}\sqrt{b} - \operatorname{arc\,tg} u^{1/3}\sqrt{b}\right)\right], \tag{6}$$

$$z = ga\{\tau - a[1 - \exp(-\tau/a)]\}. \tag{7}$$

Having set the value of u, we find τ from (6), and then, from (7) and (8) we find the coordinates x and z of the corresponding point on the "ballistic" trajectory.

From (1), (6), (7), and (8) we calculated values of x corresponding to the test conditions and the values of the radius of the circular trace R_c when z = 9 cm (for 16 000 rpm when z = 3 cm). Figure 2 shows the calculated values of R_c (continuous curve) compared with the experimental values of the mean radius R_m of the dense part of the circular trace. The root mean square deviation of R_m from R_c is 9.2%, i.e., the agreement is satisfactory.

The results of tests in [1], when similarly processed, also gave approximate agreement between calculated and measured trajectories (deviations within 30%).

The data of [6] also gave similar results.

Thus, it may be considered reliably established that, under conditions corresponding to the test range of measurement of the parameters, the basic droplets thrown off from the periphery of the disc move in trajectories close to "ballistic," i.e., in trajectories corresponding to the motion of a solid sphere of the same size and density through still air, starting with a velocity equal in magnitude and direction to the circumferential velocity of the disc.

The motion of droplets in ballistic trajectories and the agreement of their diameters with (1) obviously confirms the absence of so-called "secondary" subdivision of droplets thrown off from the rim of the rotating disc. Therefore, analysis of trajectories of droplets formed by a disc atomizer may allow conditions to be determined under which "secondary" subdivision of droplets is absent (or, on the other hand, is present), i.e., the possibility of studying the phenomenon experimentally.

The numerical conditions of subdivision are assumed to be described by the Weber number, which is the ratio of the dynamic pressure of the medium to the capillary pressure. It is customary to consider that subdivision occurs on reaching a critical value of We, for which values from 1.7 to 7.5 have been obtained by various authors [9-15].

Assuming expression (1) for d, we obtain, for a centrifugal atomizer,

$$\mathrm{We} = C \rho_a \omega D^{3/2}/8 (\rho_l \sigma)^{1/2}. \tag{8}$$

By increasing ω or D, we may obtain values of We substantially greater than the critical values obtained in [9-15]. Calculation shows that tests of atomization of liquids by rotating discs or rotors, results of which have been published, were carried out at values of We not exceeding 5.2. In these tests, agreement of droplet diameter with (1) was maintained, and (according to our calculations) the droplet trajectories were close to "ballistic"; therefore, in these tests there was no mass subdivision of droplets in the air.

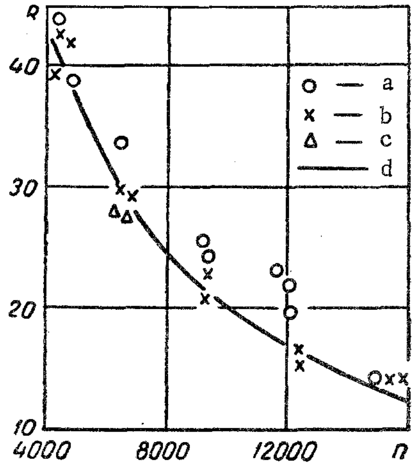

Fig. 2. Measured and calculated values of radius of circular trace R: a, b, c) See Fig. 1; d) according to (1), (5), (6), and (7) with C = 4.0.

To obtain We values greater than had been utilized by other investigators, we carried out supplementary tests with disc diameter increased by a factor of two (D = 14.0 cm), and with the rate of rotation increased to 19 000 rpm. The results of the tests and calculated values of We, C, R_c, and R_m are given in Table 1. It can be seen from the table that the basic droplets evaluated (deposited within the control ring) comprise about half of all the atomized liquid ε = 40.5-57%. The constant C varied from 3.80 to 4.45 and averaged 4.08, i.e., its values did not change appreciably.

The values of the "ballistic" radius R_c of the circular trace were close to the previously measured values (discrepancy up to 19%). This means that mass subdivision of droplets in the air did not occur in any of the tests conducted, in spite of the fact that these tests were carried out at values of critical We up to 13.0, i.e., appreciably higher than the critical values obtained in [9-15].

The reason is probably that the complex process of subdivision of droplets cannot be uniquely determined by the single parameter, We. In geometrically similar systems, subdivision of droplets moving in a gas or liquid medium is characterized not by one, but by five determinant dimensionless parameters* in accordance with the number of given dimensions and with the π-theorem of similarity theory. Moreover, the systems used in the tests by different authors are not geometrically similar so that some influence may be exerted by additional parameters characterizing the difference between the systems examined.

Table 1

Results of Supplementary Tests

Flow rate of liquid, cm^3/sec	n, rpm	ε, %	d, micron	Root mean square deviation α, %	C	R_m, cm	R_c, cm	We
0.041	7200	49.5	89.5	8.52	4.15	31.0	33.6	4.5
0.041	9800	45.0	62.5	9.10	3.94	21.0	21.5	5.8
0.045	12 000	57.0	49.1	6.62	3.80	18.0	15.1	6.9
0.042	15 800	40.5	40.2	10.60	4.06	15.0	12.9	9.8
0.065	19 000	—	36.8	10.70	4.45	13.5	11.7	13.0

Table 2 gives the critical values of the characteristic parameters We, Re, La, M, N. In [12] the value of M varies in the range 670-11 300; however, judging from the results of the tests, this is not of decisive significance. On the other hand, in [16] a low value of M evidently proved decisive. In the remainder of the tests the values of M were close to one another. The large value of N in the tests of [13] with droplets of glycerin was the reason for inhibition of subdivision. The value of Re describing the motion of the medium evidently plays a decisive role in the tests of [16], where turbulent fluctuations of the medium (liquid) were the cause of subdivision; in the remainder of the tests it apparently had a minor effect.

There is a conspicuous and sharp difference in the value of La in the tests of [9-13], where subdivision occurred (La = 0.151-0.48), and in the tests with centrifugal atomization [1] and the present tests, where there was no subdivision (La = 82, 104). The La number is the ratio of the forces of viscous friction retarding deformation of the droplets to the forces of surface tension; increase of La is evidence of an increase in the role of viscous forces in inhibiting subdivision.

*It is known that the system of determinant parameters is found by developing the corresponding equations and conditions of uniqueness by methods of similarity theory or by dimensional analysis.

We shall try to present the role of these forces more clearly.

The process of decomposition of droplets goes on with time; the friction forces within the droplet retard this process. Under centrifugal atomization (and generally in the motion of a droplet in air with a large initial velocity), the velocity of the droplets relative to the air falls rapidly; the dynamic pressure deforming the droplet falls even more quickly. Subdivision begun at a high pressure is inhibited at a low pressure. If the duration of the action of high pressure on the droplet is less than the time required for disintegration, the latter will not take place. Because of the reduction of the deforming forces under the influence of forces of surface tension, the droplet again takes its initial spherical shape.

Table 2

Critical Values of Characteristic Parameters

Tests	We	La	M	N	Re	T	Subdivision
Volynskii [12]	5.35— —7.00	0.185— —0.206	670— —11300	0.0076— —0.0640	—	16 400— 470 000	Yes
Lane [9]	5.10	0.151— —0.480	834	0.0640	—	8000— 19 000	"
Bukhman [10]	1.70— —5.20	0.115— —0.155	834	0.0640	1480— —8300	22 000	"
Merrington and Richardson [13]	7.50	0.137	834	0.0640	—	very* large	"
Merrington and Richardson [13] (glycerin droplets)	7.50	—	1050	69	—	"	"
Baranaev, et al. [16]	0.05	0.010	1.0	0.85— —2.00	6150— —43500	"	"
Walton and Prewett [1]	5.20	104	872	1.58	—	11.5	No
Present tests	13.0	82.0	743	1.39	—	16.4	"

*For tests [13] and [16] the quantity $T = \tau_h/\tau_s$ cannot be determined from (9), which is only applicable for droplets moving with a large initial velocity relative to the medium.

Thus, the fate of a droplet must depend on the ratio of the characteristic time of motion of the droplet with high relative velocity (τ_h) to the time characterizing the duration of disintegration of the droplet (τ_s) under the given conditions. We arrive, therefore, at the new criterion $T = \tau_h/\tau_s$.

Then, to evaluate time τ_h, we use (5). We take τ_h to be the time required for the initial velocity of the droplet to fall by a factor of two, i.e., $u_0/u = 2$. According to Levich [15], the time required to deform and divide a droplet of viscous liquid in motion relative to air, is $\tau_s \sim \rho_l \nu_l d/\sigma$. After a simple transformation, we obtain

$$\tau_h/\tau_s \sim T = \frac{\mathrm{We}}{\mathrm{La}^2} M^2 N \lg\left(1+\frac{3.54}{6+\frac{\mathrm{We}}{\mathrm{La}}MN}\right) \approx \frac{3.54M}{\mathrm{La}\left(1+\frac{\sigma\,\mathrm{La}}{\mathrm{We}\,MN}\right)}, \quad (9)$$

i.e., the dimensionless time required for disintegration decreases with increase of La, and increases with increase of We, M, and N.

The values of T obtained by various authors are given in Table 2. It may be seen that, in the tests of [9-13], where subdivision of droplets was observed, the values of T were hundreds of times greater than in our tests. It is probable that this was also a reason for the absence of subdivision in our tests, since, in spite of the high values of We, the duration of motion of a droplet with high relative velocity under centrifugal atomization proved to be insufficient for subdivision of droplets in air. With increase of the circumferential velocity u of the disc and of its diameter D, the We number increases, but at the same time La increases and T decreases, and it is therefore possible that even further increases of u and D under centrifugal atomization with small mass flow of liquid does not lead to subdivision of the droplets in air.

It may thus be concluded that the parameter T plays the main role in the subdivision of droplets. It is probable that taking this parameter into account would also throw light on other facts connected with the disintegration of a liquid which have not yet been explained.

NOTATION

d – diameter of basic droplets; C – a constant depending mainly on the properties of the liquid; D – disc diameter; ω – angular velocity of rotation of disc; σ – surface tension of liquid; ρ_l – density of liquid; ρ_a – density of air; ν_l – viscosity of liquid; ν_a – viscosity of air; ε – relative mass of basic droplets deposited within control circle; m – mass of drop; u, ω – horizontal and vertical components of velocity of droplet relative to air; τ – time; g – acceleration due to gravity; F_x, F_z – horizontal and vertical components of air resistance; ψ – resistance coefficient; R_c and R_m – calculated and measured values of radius of circular trace; n – number of revolutions of disc per minute; $a = d^2 \rho_l / 18\nu_a \rho_a$; $b = 0.167 (d/\nu_a)^{2/3}$; $We = \rho_a u^2 d/2\sigma$; $La = \rho_l \nu_l u/\sigma$; $M = \rho_l/\rho_a$; $N = \nu_l/\nu_a$; $T = \tau_h/\tau_s$; τ_h – time of motion of droplet with high relative velocity; τ_s – time required for deformation and subdivision of a droplet.

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Phytopathology Institute,
Moscow