PRODUCTION OF UNIFORM DROPLETS BY A ROTATING PERFORATED DRUM

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A method is given for calculating the basic characteristics of droplet dispersion by a rotating perforated drum.

It is usual in spraying a liquid to attempt to obtain droplets of a certain optimal size, but most spraying devices produce polydisperse droplet systems with a wide side range not capable of control. This gives interest to rotating sprayers, which under certain conditions provide uniform droplet size [1-3].

Detailed studies have been made of the physical droplet-production mechanism mainly for rotating disks.

It has been found that a liquid directed as a continuous jet onto the center of a rotating smooth disk, which it wets well, flows over the surface as a thin axially symmetrical film whose parameters can be calculated.

If the flow rate is very low (first state), approximately identical primary droplets are formed at the edge of the disk, together with smaller satellite droplets. The proportion of main droplets falls as the flow rate increases, while that of the satellite droplets increases, and then the first state is replaced by the second, in which continuous liquid filaments are formed at the edge rather than individual droplets. These filaments split up into secondary droplets uniform in size. Any further increase in flow rate gives rise to the third (polydisperse) state, where the edge of the disk throws out not filaments, but a film, which splits up into droplets of various sizes.

A survey of these studies has led to a method of calculation in which one can predetermine the approximate values for the basic parameters [4]. Practical use has shown that this greatly accelerates the design of suitable apparatus with appropriate parameters [5].

However, rotating smooth disks are not the only sprayers in common use, since others such as perforated drums are also widely employed.

Empirical relationships exist for the mean diameter produced by these devices at high flow rates (polydisperse spraying [6]). However, a perforated drum is also of considerable interest for producing monodisperse systems. Such devices, if made of chemically resistant plastic, enable one to spray any liquid, including corrosive ones and ones that do not wet the drum.

However, nothing has been published on the physical mechanism for such drums, and no suitable methods of calculation are available. One assumes that the process is similar to that of droplet formation by a smooth disk, and the phenomena observed at the edge of the disk will occur also at the edges of the holes. Therefore, at the edge of such a hole one will get the first, second, or third states in accordance with the flow rates. One expects that the similarity between the processes would allow one to devise a method of calculating the performance of a perforated drum similar to the existing method for a disk.

We checked out these assumptions on rotating perforated drums operating with monodisperse systems; Figure 1 shows the system.

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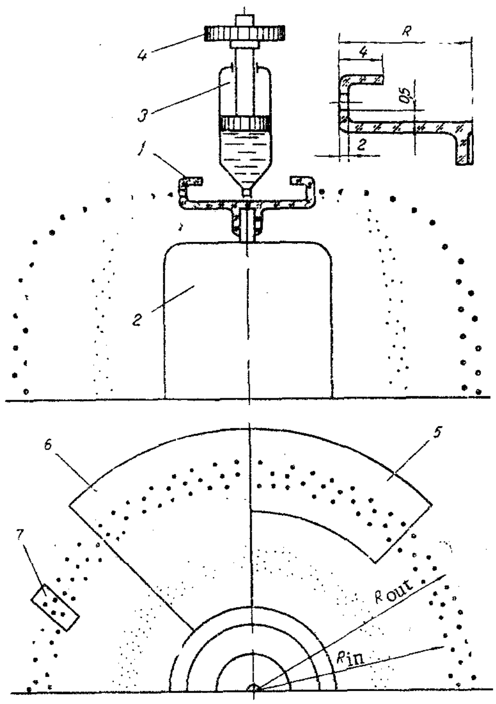

Fig. 1. The apparatus.

The center of the perforated drum 1, which is driven by the synchronous electric motor 2 (n = 3000, 1500, 1200, 695 rpm), is supplied with liquid from the needle of the syringe 3, whose shaft was loaded by the weight 4. To produce the very low flow rates corresponding to the monodisperse state the needle was placed near the inner surface of the drum to give a gap of about 0.2 mm. The liquid flowing from the needle did not then accumulate as large droplets at the end, but flowed continuously away over the inner surface. The perforated drums were made of Lucite and had outside diameters of R = 1.1; 2.5; 3.5; 5; 7.5 cm and hole diameters of r = 0.3; 0.65; 0.8; 1; 2; 4 mm; the numbers of holes ranged from 1 to 70, and they always formed a single row. The speeds were n = 695; 1200; 1500; 3000 rpm, and the flow rates were Q = 0.0008–2.5 cm^3/sec. The working liquid was transformer oil (ρ = 0.892 g/cm^3; ν = 0.218 cm^2/sec; σ = 33 g/sec^2), or else Vaseline oil (ρ = 0.89 g/cm^3, ν = 1.489 cm^2/sec, σ = 30 g/sec^2), or lubricating oil (ρ = 0.897 g/cm^3, ν = 2.64 cm^2/sec, σ = 29 g/sec^2).

Visual observations were made with an ST-5 strobotachometer and confirmed our assumption that the droplets were produced at the edge of each hole in the way previously observed on a disk in the first state, i.e., the individual droplets were produced directly at the edge and broke away. Further, the second state could be observed on increasing the flow rate, with the formation and breakup of liquid filaments.

In the first state, as with a disk, the liquid accumulated along the edge as a ring, which was unstable and was distorted by random perturbations. The wavelength λ (distance between adjacent deformed parts) was measured in the visual observation and was close to the values calculated for disks [2]. In the second state, the number of filaments also was close to the value $z = 2\pi r/\bar{\lambda}$ calculated for a disk.

As in the case of the experiments with the smooth disk, the main droplets of colored liquid produced a narrow ring of regular shape on a horizontal sheet of white paper, which showed that the main droplets were uniform in size. The smaller satellite droplets were deposited within the latter. As in the case of the smooth disk, the sharp ring formed by the main droplets became paler as the flow rate increased (without change of radius) till it ultimately vanished, i.e., the proportion of main droplets fell. The inner ring formed by the satellite droplets became denser, i.e., the proportion of satellites increased. The mean radius of the inner ring gradually increased, i.e., the mean size of the satellite droplets rose.

In exact measurements on the above states, we determined the arithmetic mean diameter of the main droplets $\bar{d}$, the outside and inside radii of the ring of droplets R_{dr}, and the amount (by weight) of the satellite droplets.

To determine the proportion by weight of the main droplets with a virtually nonvolatile liquid, we measured the increase in weight ΔG of the paper ring 5 (Fig. 1) on which they were deposited. The total

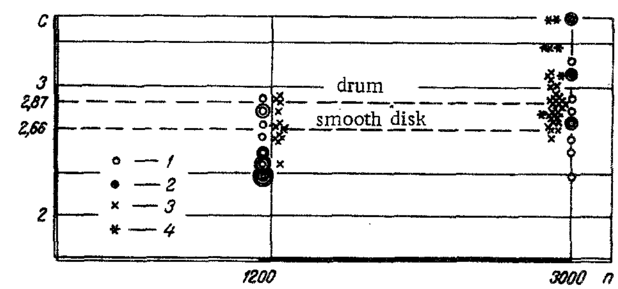

Fig. 2. The values of C for: 1 and 2) smooth disk with transformer oil and lubricating oil, respectively; 3 and 4) drum with the same.

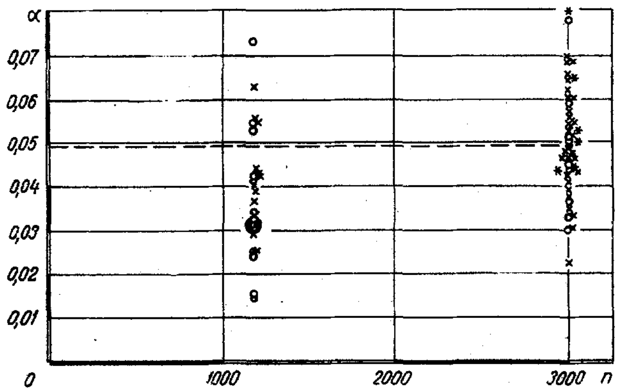

Fig. 3. Dimensionless standard deviations of main drops from the mean for disk and drum. Symbols as in Fig. 2.

amount of liquid supplied was determined from the increase in weight G_0 of the ring 6. The proportion by weight of main droplets was $E = \Delta G/G_0$. The result for G_0 was checked from the amount of liquid leaving the syringe 3. We also measured the outside and inside radii of the ring formed by the main droplets.

The sizes of the main droplets within the ring were determined with glass slides 7, which were exposed during the experiment for several seconds. The glass had previously been coated with a layer of silicone to provide a constant wetting angle for the droplets. The droplets were examined and counted under the microscope. Figures 2-5 give the results.

The results were processed to show that the diameter of the main droplets in the first state is given by the following formula:

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

where the values of the constant C in this formula were similar for drum and disk throughout the range in the parameters (n = 1200-3000 rpm, R = 1.1-5 cm, hole diameter 0.8-4 mm, σ = 29-33 g/sec^2, ν = 0.218-2.64 cm^2/sec) (Fig. 2). The values of C for disk and drum were statistically identical: C = 2.8.

Figure 3 shows the dimensionless standard deviations of the droplet diameters d:

$$\alpha = \beta/\bar{d}. \tag{2}$$

The values of α for a smooth disk and for a perforated drum were statistically the same.

The drum and disk were compared as regards proportion of satellite droplets using the results for the drum and calculations from our empirical formula [7] for a smooth disk:

$$E = 86\,\frac{\omega^{0.48}\nu^{0.12}R^{0.32}}{}\left(\frac{\rho Q}{R\sigma}\right)^{0.62} \leqslant 100\%. \tag{3}$$

Visual observation indicated that the processes in the two cases were identical, and so the R for the disk in the quantity in parentheses on the right in (3) was replaced by the product of the number of holes n and the radius of a hole r.

Figure 4 shows the calculated E plotted horizontally and the observed ones, vertically. The number of satellite droplets formed per unit length of edge under identical conditions was somewhat greater than that for a smooth disk.

The form taken by (3) for a perforated drum is

$$E = 100\,\frac{\omega^{0.48}\nu^{0.12}R^{0.32}}{}\left(\frac{\rho Q}{nr\sigma}\right)^{0.62} \leqslant 100\%. \tag{3a}$$

Formulas (1) and (3a) can be recommended for calculating a perforated drum for the first mode of spraying.

One can assume, as for a smooth disk, that the condition for transfer from the first state to the second is E = 100%, in which case one can use (3a) to determine the range of parameters corresponding

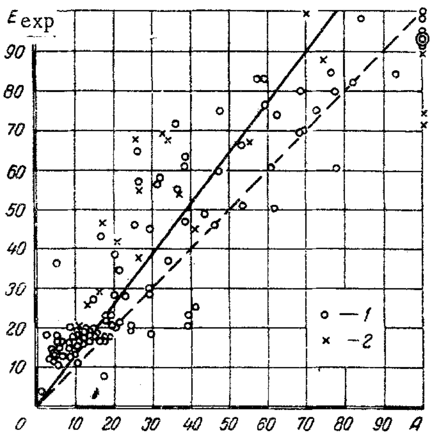

Fig. 4

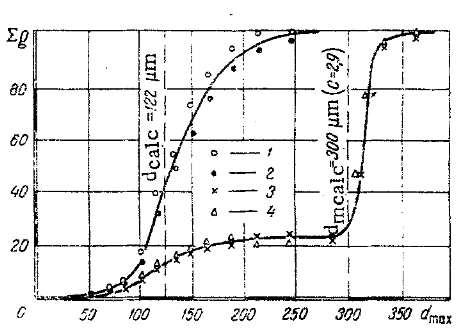

Fig. 5

Fig. 4. Calculated and measured proportions of auxiliary drops at n of 1500–3000 rpm for perforated drum: 1) transformer oil; 2) lubricating oil.

Fig. 5. Observed and calculated drop-size distributions for disk and drum at $\omega = 314\ \mathrm{sec}^{-1}$, n = 70 holes, r = 0.05 cm, R = 3.5 cm, nr = R: 1 and 2) Q = 0.97 $\mathrm{cm}^3/\mathrm{sec}$ for disk and drum, respectively; 3 and 4) Q = 0.1 $\mathrm{cm}^3/\mathrm{sec}$ for the same. d_{max} in μm, Σg in %.

to the first state (E ≤ 100%) and the second one (E > 100%); this was confirmed in tests on the size distributions of the droplets from disk and drum; virtually identical distributions were obtained (Fig. 5) at a given flow rate per unit length of edge in the first state (E = 25%) and in the second one (E > 100%).

It follows from (3a) that one can reduce the number of satellite droplets by increasing the number of holes or the size of the holes. This is one of the advantages of a drum sprayer.

A considerable increase in output could be obtained by increasing the number of rows of holes, but this would require identical flow rate through each individual hole, which would lead to design difficulties. If measures are not taken to provide identical flow rates, we found that there was no point in using more than two rows of holes, since even the third row (with 70 holes in each row) produced a proportion of main droplets much less than for two rows.

The mean droplet diameter for a liquid of low viscosity dispersed by a smooth disk in the second state is [2]

$$d_m = 1.48 \left(\frac{Q\sigma}{\rho\omega^2 R^{5/2}}\right)^{2/7}. \tag{4}$$

The following formula is applicable for very viscous liquids:

$$d_m = 2.12\, \frac{\sigma^{0.27} Q^{0.306} \nu^{0.11}}{\rho^{0.27} R^{0.725} \omega^{0.84}}. \tag{5}$$

Calculations from these formulas can be compared with experiment by replacing Q/R by Q/nr, and we found that the formulas are applicable to a perforated drum in the second state.

Figure 5 compares the observed size distributions and the calculated mean d_{calc}.

The formulas for the paths taken by drops from the edge of a smooth disk [1] are also applicable to a perforated drum.

Visual observations indicate that the mechanism of transition from the second state to the third (polydisperse state) is that the individual liquid filaments fuse into a cylindrical film, which is analogous to the planar film produced by a disk. The condition for transition to the third state has not yet been examined quantitatively.

As regards the visual observations, we may note that at very low drum speeds one gets the following effect: the droplets are formed not at the edges of the holes, but below the edges, in the lower part of the outer cylindrical surface; it is clear that in this case, where the centrifugal forces are small, gravitational forces come to predominate.

One can use the ratio of the centrifugal and gravitational forces K to characterize this state:

$$K = \frac{\omega^2 R}{g}, \tag{6}$$

and then observations would indicate that the gravitational state (droplets formed below the edge of the holes) occurs for $K \leq 10$, while droplets are formed all along the edge (first state) for $K \geq 50$; the region $10 < K < 50$ is transitional.

It follows from (1) and (6) that

$$d_{\text{grav}} = C \left(\frac{\sigma}{K \rho g} \right)^{1/2} \tag{7}$$

The minimum values of d for the gravitational state (K = 10) are about 1.7 mm for oils, i.e., the gravitational state produces very large droplets.

NOTATION

R, ω	are the radius and angular velocity of drum;
n, r	are the number and radius of holes;
Q, ρ, ν, σ	are the flow rate, density, kinematic viscosity, and surface tension;
E	is the proportion by weight of auxiliary droplets;
C	is the dimensionless constant;
g	is the acceleration due to gravity;
α	is the coefficient of variation;
β	is the standard deviation;
d	is the mean diameter of main droplets;
d_m	is the mass-median diameter of secondary droplets (second state).

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