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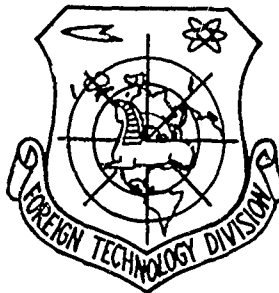# FOREIGN TECHNOLOGY DIVISION

METHOD OF DETERMINING THE DROPLET
SIZE DISTRIBUTION IN THE
ATOMIZATION OF LIQUIDS

by

V. F. Dunskiy and N. V. Nikitin

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UR/0170-67-012-002

Date 5 Sep 19 68

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DATA HANDLING PAGE

01-ACCESSION NO.	98-DOCUMENT LOC	39-TOPIC TAGS
TP8501610		droplet atomization, fluid density, fluid density measurement

09-TITLE METHOD OF DETERMINING THE DROPLET SIZE DISTRIBUTION IN THE ATOMIZATION OF LIQUIDS

47-SUBJECT AREA

20

42-AUTHOR/CO-AUTHORS	10-DATE OF INFO
DUNSKIY, V. F.; 16-NIKITIN, N. V.	--FEB67

43-SOURCE	68-DOCUMENT NO.
INZHENERNO-FIZICHESKIY ZHURNAL (RUSSIAN)	FTD-MT-24-293-68
	69-PROJECT NO.
	6040104

63-SECURITY AND DOWNGRADING INFORMATION	64-CONTROL MARKINGS	97-HEADER CLASN
UNCL, 0	NONE	UNCL

75-REEL/FRAME NO.	77-SUPERSEDES	78-CHANGES	40-GEOGRAPHICAL AREA	NO. OF PAGES
1886 1060			UR	12

CONTRACT NO.	X REF ACC. NO.	PUBLISHING DATE	TYPE PRODUCT	REVISION FREQ
	65-AP7010423	94-00	Translation	NONE

STEP X:	ACCESSION NO.
02-UR/0170/67/012/002/0254/0262	

ABSTRACT
    A laboratory method was developed for determining the droplet size distribution produced by atomizers. The atomizer is placed in a tube in which air is flowing at a velocity of 10 m/sec. The droplets flow downstream around a rod which has one flat surface covered with soot and a thin layer of magnesium. The rod is enclosed in a cylindrical shutter which can be rapidly opened to expose the soot-magnesium surface to the droplets which upon impact leave traces which can be studied microscopically. The instrument was tested with glycerine-water mixtures and an aerosol generator. The droplet distributions obtained were in good agreement with measurements made by two other methods.

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.
The use of diacritical marks is preferred, but such marks
may be omitted when expediency dictates.

METHOD OF DETERMINING THE DROPLET SIZE DISTRIBUTION
IN THE ATOMIZATION OF LIQUIDS

V. F. Dunskiy, N. V. Nikitin

It is shown that the developed stand method
of atomizer tests permits correctly determining
not only the relative, but also the absolute
value of size distribution parameters of the drop-
lets which form.

The effectiveness of atomizers used for liquid dispersion in
different technical processes depends on the droplet size distribution.
However, the determination of this range involves considerable
difficulties. These difficulties necessitate the use of high-speed
locks (shutters), distorting the local droplet size distribution [1],
necessitates determining the averaged droplet size distribution for
the aerosol spray (jet) with respect to the results of local measure-
ments, errors due to possible breaking up of the droplets against the
intake surface, inaccuracies of the generally accepted microscopic
method of calculation and measurement of droplets etc.

We have developed a stand method of determining the droplet size
distribution during atomizer tests. This method, founded on deposition
of drops on the intake surface with the application of a high-speed
lock, is obviously not free from the distorting influence of the above
factors. In order to estimate the total influence of these factors,
i.e., degree of authenticity and accuracy of the stand method, we

measured the droplet size distribution of a standard aerosol not only
by this method, but also by two others which differ in principle.
Below a short description of the methods and the results of comparison
are given.

Setup for stand method. On frame 1 (Fig. 1) is wind tunnel 2
with radius R_0 = 375 mm and length of working part 2400 mm. Axial fan
3 creates in it an airflow with an average speed of 10 m/s, adjustable
with the help of diaphragm 4. In the rear of the tunnel, vertical to
the diameter, is placed tube 5 of diameter D = 12 mm, freely sliding
in wall guides. Inside tube 5 is rod 6, whose end is fastened to
bracket 7. In tube 5 is rectangular hole 8, turned toward the airflow.
The flat working surface of rod 6 (length 700 mm and width 5 mm) is
also turned toward the flow and preliminarily covered by a layer of
soot $\sim$ 1 mm thick and from above by a thin layer of magnesium oxide.
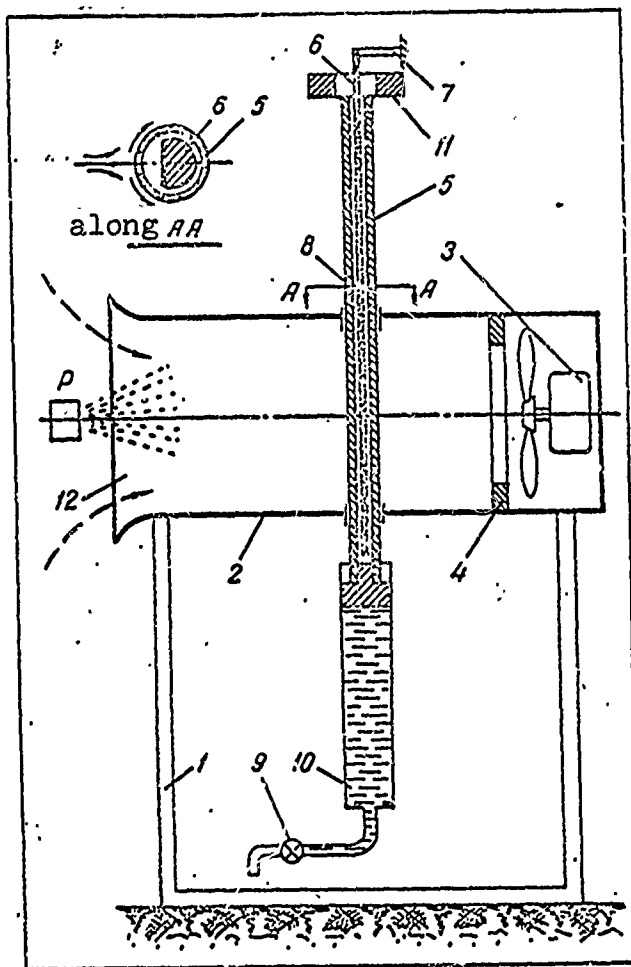

Fig. 1. Stand for atomizer tests.

Investigated atomizer P is placed on the entrance to the tunnel
and creates a jet (spray) of aerosol 12, coaxial with the tunnel.
Droplets suspended in this jet are attracted by the air and disperse
along the pipe section. Encountering tube 5, the droplets partially
flow around it together with the air, and partially — thanks to their
own inertia — strike its surface. When cock 9 is manually opened,
tube 5, joined with hydrocylinder 10, shifts under the impact of load
11 from the extreme upper position into the lower; now slot 8 exposes
the working surface of rod 6 for a fraction of a second, and the
investigated drops fall onto this surface. They pierce the layer
of magnesium oxide and form round imprints on the soot layer. Against
the background of the white layer of magnesium oxide the black imprints
are easily examined and measured under a microscope.

In steady-state atomization and considering symmetry with respect
to an axis of the tunnel, the surface computing concentrations n_i
of droplets of the i-th class (i.e., having radius from $r_{i_{min}}$ to
$r_{i_{max}}$) which have settled on rod 6 are equal to the flow per second of
these droplets per unit area of the middle section of tube 5 multiplied
by the exposure time and the coefficient of capture:

$$n_i = u_i(R)\, c_i(R)\, \tau \alpha_i.$$

The total number of droplets of the i-th class formed by atomizer
through time τ is found by integrating over the cross section area of
tunnel 2:

$$N_i = \frac{2\pi}{a_i} \int_0^{R_0} R n_i(R)\, dR. \qquad (1)$$

The working surface of the exposed rod, split into 14 sections
each 50 mm long, is examined under a microscope. On every section a
3 × 50 mm strip is examined; the imprints of 100 drops are calculated
and measured and the sizes divided into classes considering the
examined area (which the preparation carrier determines). The

remaining part of the strip is examined for the imprints of bigger drops. The relative part by weight of every class of drops g_i is found by a formula similar to (1). The values of the coefficient of capture $\alpha_i = f(Stk_i)$ [1] in this formula, considering incomplete deposition of droplets on the rod because of the entrainment of part by the streamlining air, are approximately determined by a Langmuir and Blodget graph for flow around a cylinder ([2], Fig. 46). We will use this graph for case of equality of the velocity of drops and air before the cylinder; in our case the velocity of large drops $u_i(R)$ before tube 5 can essentially exceed the velocity of air u_n. However, with the given stand parameters α_i is essentially less than one only for very fine drops (r_i < 30 μm); calculations of the motion of these drops (analogous to that given in [3]) show that under typical conditions velocity $u_i(R)$ of these drops before the tube is close to the velocity of air u_n, in the expression for Stoke criterion. Consequently, from this point of view use of this graph is legitimate).[1] In the case of a hydraulic atomizer velocity of air u_n is approximately constant across the diameter of pipe 2 and is equal to the average velocity of air in it, i.e., 10 m/s. In the case of an air-jet atomizer of low power the turbulent jet of aerosol formed by it spreads inside pipe 2 in an accompanying flow of air. If the increase of air velocity on the axis of tunnel 2 before tube 5 caused by this jet is insignificant (for example, does not exceed 30%), then during the determination of α_i it is disregard; otherwise the air velocity profile in the tunnel is determined and local values of α_i are calculated in accordance with this profile.

Pipe radius R_0 is selected so that at a given length of the working part and average air velocity of 10 m/s the largest droplets (with a radius up to 200 μm) cannot settle on its bottom before meeting tube 5. If it is necessary to work with bigger drops one should change the arrangement of the stand, for example, set up pipe 2 vertically.

Settling of drops somewhat disturbs the symmetry of the process; to decrease the influence of settling the values of n_i are determined as the average for every pair of rod sections, upper and lower, equidistant from the pipe axis.

Velocity of tube 5 and width of rectangular hole 8 should be selected so that the biggest ratio of total area of droplet imprints to the area of the working surface of rod 6 is 0.05-0.1; the probability of two different droplet imprints merging is sufficiently small. At a liquid flow rate of 3 ℓ/min, an average radius of drops of 25 μm and average hole width of 4 mm, the displacement rate tube 5 must be 0.2-0.4 m/s.

The method of determining drop size by the imprints forming on a surface covered by a layer of soot or magnesium oxide is well-known and frequently used. According to results of experiments, independently of the physio-chemical properties of the liquid when the thickness of the layer of soot, exceeds the drop radius by three times and the drop velocity is 5 m/s and more for drops whose radius exceeds 10 μm, the ratio of imprint radius r_u to drop radius r according to [4] ∿1.0 and according to [5] ∿1.20. We accepted $r_u/r = 1.1$.

As standard atomizer a farm aerosol generator AG-L6 with angular nozzle was used [6]. Liquid (water-glycerine mixture, containing 60% glycerine) passed by gravity flow into the narrow section of the Venturi nozzle through the jet and was atomized by a high-speed flow air, which was forced through the nozzles by a blower with gasoline drive motor. The diameter of the nozzle outlet was 80 mm; velocity in this section was 27 m/s.

The second method of determining the drop size distribution called for settling in a closed location [7]. For this purpose a concrete storage facility 11 × 11 × 3.5 m was used. A motor vehicle with working generator AG-L6 traveled at 9 km/hr outside past its opened door. From the generator nozzle, directed horizontally to the door, a relatively small amount of drops went through the door and settled on the floor. At 100 points on the floor glass plates covered by a thin silicone layer had been placed [8]. After the experiment the plates were microscopically examined, the size distribution of the settled drops was determined (taking into account the area of the floor covered by each plate) and its equivalent to the size distribution of drops formed by the atomizer was taken.

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In the third method [7] the drop size distribution was determined by deposits of an aerosol wave in field conditions during a very weak wind (∿0.2 m/s) and stable state of the surface layer of atmosphere (inversion). An AG-L6 generator, placed on a motor vehicle, moved around the edge of the experimental site (500 × 500 m) approximately perpendicular to the direction of the wind, creating an aerosol wave which ran into the wind on the experiment area. Nozzles were directed horizontally (perpendicularly to the direction of motion) to the wind at 1.6 m above the ground. There were 209 control points on the experiment area,[2] in each of which a silicone-coated glass plate was placed on the ground. After the experiment the plates were microscopically examined in the same way as with the second method.

There were in all eight experiments: four (No. 1-4) with the stand method, three (No. 5-7) using the settling of drops in a closed location and one (No. 8) with the field method. Conditions of the experiments are shown in Table 1.

Table 1.   Conditions of experiments.

No. experiment	Operating conditions: rotation rate of generator blower, rpm	flow rate of liquid, kg/min	Parameters of liquid $\rho_\text{ж}\cdot$, g/cm³	$\eta_\text{ж}\cdot10^3$, N·s/m²	$\sigma\cdot10^3$, N/m	temperature, °K	Barometric pressure, kN/m²	Temperature of ambient air, °K	Method of determining size distribution	Total amount of measured drops
1	2250	3,60	1,17	11,0	60	290	98,8	291	stand	1400
2	2270	3,60	1,17	11,0	60	290	98,8	291	»	1400
3	2250	3,55	1,17	11,0	60	290	99,2	292	»	1400
4	2280	3,55	1,17	11,0	60	290	99,2	292	»	1400
5	2200	3,45	1,17	11,8	61.	296	93	299	in closed location	10000
6	2200	3,60	1,17	11,8	61	296	92,5	297	»»	10000
7	2200	3,55	1,17	11,8	61	297	93,6	298	».	10000
8	2200	3,50	1,16	11,0	59	296	92,6	296	in field	20000*

*The great amount of drops measured in the field experiment is caused by the necessity of smooth the fluctuation aerosol deposits (see [9]).

From the table it is clear that during stand experiments the barometric pressure somewhat exceeded that in remaining experiments, and the temperature of air and liquid was somewhat less; probably,

these deflections partly compensated one another from the point of view of quality of atomization. In other respects conditions were practically identical. In the second and third methods the quantity of measured drops many times exceeded the amount in the first method.

Results of experiments — empirical distributions of the weight of atomized liquid with respect to droplet size — are given in Table 2. From this table it is clear that in the field experiment (No. 8) a "tail" of large drops with a radius from 250 to 416 µm was obtained, composing, however, only a small part of the liquid by weight (near 1%). In experiments No. 5-7 (the location) the biggest detected drops had a radius of 250 µm, and in stand experiments — only 150 µm. However, in all experiments the part by weight of liquid in the droplets of radius exceeding 150 µm was small (not more than 9%), i.e., noted distinctions from the point of view of amount are secondary.

A quantitative comparison of obtained empirical distributions is simplified if a theoretical law would be known . t least approximately describing them. This question itself presents great independent interest.

We assumed that when liquid was split by a high-speed air flow in the nozzle of the AG-L6 generator the size distribution of the forming droplets is approximately described logarithmically by normal law, i.e., that distribution density of the weight of liquid by the logarithm of the radius of droplets

$$G(\lg r) = \frac{1}{\lg \delta \sqrt{2\pi}} \exp\left[-\frac{(\lg r - \lg r_m)^2}{2(\lg \delta)^2}\right]$$

or

$$F(\varepsilon) = \int_{-\infty}^{\varepsilon} G(t)\,dt = \frac{1}{2}\left[1 + \frac{2}{\sqrt{2\pi}} \int_{0}^{\varepsilon} \exp(-t^2/2)\,dt\right] =$$
$$= \frac{1}{2}[1 + \Phi(\varepsilon)], \tag{2}$$

Table 2. Experimental distribution of droplet size.

Experiments No. 1, 2, 3, 4 (stand measurements)

r_i, μm	7	13,5	20,5	27,5	34	40,5	51	65	78,5	92	105,5	119	133	147
$r_{imin} \div r_{imax}$, μm	3,5—10	10—17	17—24	24—31	31—37	37—44	41—58	58—72	72—85	85—99	99—112	112—126	126—140	110—151
g_i, % Exp. № 1	1,00	4,10	9,08	11,1	6,69	5,62	12,1	13,5	8,45	9,35	6,46	1,59	8,57	2,45
Exp. № 2	1,80	5,13	9,67	9,57	9,56	5,75	16,9	14,7	8,95	5,30	6,25	4,06	—	2,46
Exp. № 3	1,33	3,31	7,10	7,61	6,77	5,13	18,0	14,2	11,2	12,1	8,74	1,08	3,53	—
Exp. № 4	0,88	5,80	14,6	16,2	7,25	5,26	11,5	13,8	8,80	5,93	6,03	2,45	1,70	—

Experiments No. 5, 6, 7 (measurement in location)

r_i, μm	6,4	12,5	21	29	38	46	54	67	83	103	116	183	210
$r_{imin} \div r_{imax}$, μm	4,2—8,5	8,5—16,5	16,5—25	25—33	33—42	42—50	50—58	58—75	75—91	91—125	125—167	167—200	200—250
g_i, % Exp. № 5	0,54	4,33	8,16	9,22	10,5	12,8	11,5	8,57	14,7	12,3	6,09	0,35	0,02
Exp. № 6	0,34	2,64	5,90	8,47	7,91	7,64	9,04	11,7	10,6	17,8	12,7	5,44	—
Exp. № 7	0,83	4,52	8,39	12,4	12,9	7,83	6,94	14,6	10,8	12,9	6,49	0,79	0,95

Experiment No. 8 (measurement in field)

r_i, μm	12,5	25	41,5	58,5	75	91,5	108,5	125	141	158	175	191	208	233	267	300	366
$r_{imin} \div r_{imax}$, μm	8,5—16,5	16,5—33	33—50	50—67	67—83	83—100	100—117	117—133	133—150	150—166	166—183	183—200	200—216	216—250	250—251	251—316	316—116
g_i, %	5,94	19,3	20,1	12,4	15,3	7,04	5,18	3,25	2,76	2,01	2,03	1,04	0,41	2,07	0,25	0,51	0,30

where

$$\lg \delta = \sqrt{\overline{(\lg r - \lg r_m)^2}},$$

$$\varepsilon = (\lg r - \lg r_m)/\lg \delta.$$

To check this assumption the empirical distributions obtained in experiments were compared with the corresponding log normal distributions. Figure 2 is the corresponding graph for experiment No. 8. The points show empirical integral distribution $\Sigma g_i = f(r_{i_{max}})$, the solid line shows log normal distribution $F(\varepsilon) = f(r)$. For both weight distributions the median radius of drops r_m = 55.1 µm, the logarithm of standard geometric deviation $\lg \delta$ = 0.314.
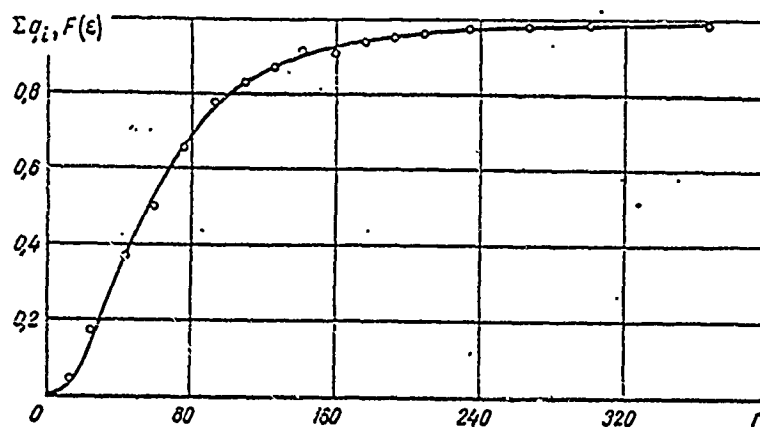

Fig. 2. Comparison of theoretical and empirical distributions. Experiment No. 8.

The graph testifies to a fully satisfactory correspondence between empirical and theoretical distributions.

Figure 3 is a similar graph for experiments No. 1-4 and 5-7. To exclude the influence of distinctions in r_m these graphs are represented in dimensionless form. Again correspondence between empirical and theoretical distributions is fully satisfactory, i.e., our assumption can be recognized as confirmed.

Thanks to this we can present the results of every experiment by the corresponding values of two parameters, determining the log normal distribution: weight median radius of drops r_m and logarithm of standard geometric deviation $\lg \delta$. Values of these parameters for
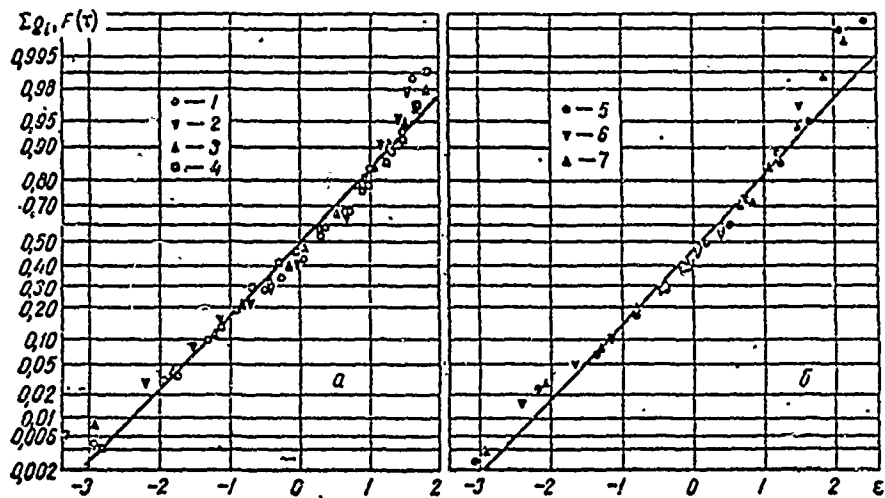
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Fig. 3. Comparison of theoretical and empirical distributions. Experiments 1-4 (a) and 5-7 (b). Numbers of points correspond to numbers of experiments.

each of the experiments are:

No. experiments	:1	2	3	4	5	6	7	8
r_m, μ^m	59,5	46,9	52,3	42,7	50,1	66,1	52,4	55,1
lg δ	0,292	0,282	0,263	0,279	0,276	0,294	0,293	0,314

Unfortunately, experiment No. 8, conducted by the field method, is unique and therefore can be used only for qualitative comparisons; however, results of experiments No. 1-4 (stand method) and 5-7 (measurement in closed location) can be compared statistically, for example, by means of dispersion analysis ([10], p. 40).

Treatment of data by this method showed that distinctions in values of r_m and lg δ, obtained in experiments No. 1-4, on the one hand, and 5-7 on the other, are statistically unreliable, i.e., these distinctions lie within the limits of measurement accuracy.

The fact that measurements of the same object conducted by methods different in principle gave statistically identical results, indicates that each of these methods, even tne stand method, gives correct results.

This signifies also that the total systematic influence of distorting factors (influence of high-speed shutter and others) is small in comparison with random errors in each of the tested methods.

Statistical analysis of data by the small sample method ([10], p. 297) showed that with triple measurement of the droplet size distribution on a stand the error in determination of r_m accurate to 90% does not exceed $\pm 20\%$. With double measurements error is excessively great; measurements must be repeated not less than three times. Values of $\lg \delta$ are determined with smaller error than values of r_m. According to results of analysis by the small sample method, accuracy of stand measurements is higher than in considerably more laborious measurements in a closed location; moreover the latter are possible only with nonvolatile liquids.

Obtained results permit recommending this stand method for practical application.

Designations

$u_i(R)$ — velocity of droplets of the i-th class at distance R from axis stand cylinder before the intake rod; u_0 — velocity of the air in stand cylinder; N_i — quantity of drops of the i-th class, created by atomizer during time τ; r — radius of drop; $r_к$ — radius of imprint of drop; r_i, $r_{i_{max}}$, $r_{i_{min}}$ — average, maximum and minimum radii of drops of i-th class; r_m — weight median radius of drops; R_0 — radius of stand cylinder; $c_i(R)$ — volume computing concentration of drops of the i-th class at distance R from axis of stand cylinder before intake rod; $n_i(R)$ — surface computing concentration of settled drops of the i-th class on the working surface of the rod at distance R from the axis of the stand cylinder; g_i — relative weight of drops of the i-th class; $a_i = f(\text{Stk}_i)$ — coefficient of capture for a drop of radius r_i during flow around the stand tube; $\text{Stk}_i = 2\rho_ж u_0 r_i^2 / 9\eta D$; $\rho_ж$, $\eta_ж$, σ — density, viscosity and surface tension of liquid; η — viscosity of air; D — diameter of stand tube; $\Phi(\epsilon)$ — probability integral; δ — standard geometric deviation; F — integral distribution function of weight of liquid with respect to logarithm of droplet radius.

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16 August 1966   Institute of Phytopathology
                                                  Moscow

Footnotes

[1] It is necessary, however, to note that this graph pertains to flow around fixed cylinder, and in our case flow is around a moving tube 5, and drops penetrate through its hole and hit fixed internal rod 6; therefore, the correction inserted using this graph is only a first approximation.

[2] The great quantity of control points is required to smooth fluctuations of the aerosol deposits [9].