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EXPERIMENTAL DETERMINATION OF FUEL-ATOMIZATION QUALITY
FROM HIGH-CAPACITY CENTRIFUGAL SPRAY NOZZLES

by

Yu. I. Khavkin



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ABSTRACT: An experimental determination has been made of the quality of fuel (solar oil) atomization by large capacity (1500 kg/hr) swirl injectors. In the experiments, the pressure before the nozzle was varied from 5 to 60 kg/cm², kinematic viscosity of the fuel from 0.04 to 0.4 cm²/sec, fuel flow rate from 123 to 1322 kg/hr, and Reynolds number from 1640 to 18,280. The quality of atomization was determined by measuring the droplet imprints on a plate coated with solar oil soot 0.5 to 0.7 mm thick. The obtained results are shown in Fig. 1. The formula $d_k/d_e = 18.3/Re_e^{0.59}$ can be used for calculating the quality of fuel atomization. English translation: 15 pages.

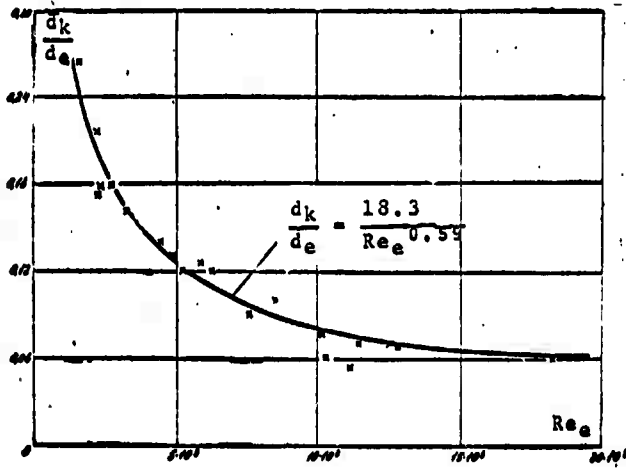


Fig. 1. Relationship $\bar{d}_k/d_e = f(Re_e)$

(Where \bar{d}_k = droplet diameter constant corresponding to a specific Re_e ; d_e = equivalent nozzle diameter.).

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EXPERIMENTAL DETERMINATION OF FUEL-ATOMIZATION
QUALITY FROM HIGH-CAPACITY CENTRIFUGAL SPRAY NOZZLES

Yu.I. Khavkin*

This paper presents results from an experimental study of fuel-atomization quality achieved with high-capacity spray nozzles. It is demonstrated that with accuracy sufficient for practical purposes the atomization quality can be evaluated on the basis of known geometric spray-nozzle parameters with respect to its flow-rate characteristic.

The phenomenon of liquid-stream atomization into drops is utilized in various branches of engineering. In designing a process (evaporation of water, combustion of drops of fuel, the desiccation of milk, etc.) of which atomization is a component element, we must have data at our disposal on the quality of the atomization.

The quality of atomization is characterized by the mean drop diameter and in the final analysis is determined by the type of spray nozzle, its dimensions, the pressure and physical properties of the liquid and of the medium into which the atomization is accomplished.

It is presently impossible to determine atomization quality theoretically. There is also considerable difficulty involved in the determination of atomization quality experimentally. None of the existing methods may be regarded as perfect. Many of these methods are associated with considerable expenditures of time and effort. This can also serve as an explanation of the fact that very little effort is devoted to the determination of atomization quality. Basically, these efforts are directed toward the determination of atomization quality from spray noz-

zles of low (below 100 kg/hr) and average capacity (below 500 kg/hr). Water is utilized frequently as the working fluid.

The present paper is devoted to an experimental determination of the atomization quality for liquid fuel (solar oil) by means of centrifugal high-capacity spray nozzles (with a capacity of up to 1500 kg/hr).

It has been established experimentally [1, 2, 3] that the distribution of drops by dimensions in a stream of atomized liquid follows the law of large numbers and is well described by the Rozin-Ramler [sic] formula derived for the case of solid-fuel fragmentation:

$$R_i = 100e^{-\left(\frac{d_i}{\bar{d}_k}\right)^n}, \quad (1)$$

where R_i is the gravimetric fraction of the stream in %, consisting of drops having a diameter larger than d_i ; d_i is the instantaneous drop diameter; \bar{d}_k is the constant of drop dimension, corresponding to a specific value of R ; n is a constant characterizing the degree of drop non-uniformity.

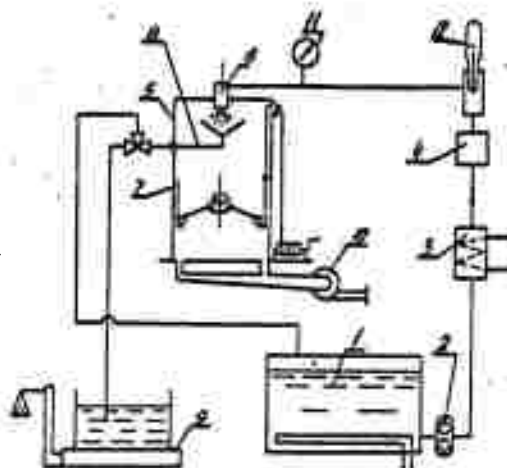


Fig. 1. Diagram showing spray-nozzle test installation: 1) Fuel tank with coil pipe; 2) screw fuel pump, $Q_{\max} = 5000$ kg/hr; $P_{\max} = 80$ gauge atmospheres; 3) fuel heater; 4) fuel filter; 5) vertical stand; 6) spray nozzle; 7) movable frame; 8) bypass tube; 9) scales, $P_{\max} = 500$ kg; 10) fan, $Q = 200$ m³/hr; $H = 200$ mm water column; 11) manometer; 12) thermometer.

This formula, successfully employed by a number of investigators to calculate the rate of evaporation for atomized fuel streams [3, 4], is utilized in the present paper. The selection of Function (1) predetermined the purpose of the investigation, i.e., the determination of the constants d_k and n in (1).

The difficulty involved in the experimental determination of the atomization quality involves, first of all, the complexities encountered in measurement of dimensions of flying drops and, secondly, in the limited number of drops in the stream which can actually be measured. In this connection, the measurement of atomization quality must be carried out at a great many points with subsequent consideration of the "weight" of each of these. The installation must therefore be provided with a device to measure the drop dimensions and the density of the spray at each point.

It will be demonstrated later on that the atomization quality of a fuel by means of centrifugal spray nozzles is governed by the flow rate of the fuel through the spray nozzle and by the pressure ahead of the nozzle; the experimental installation must therefore be equipped with a device to cut off the flow of fuel and to measure the rate of flow through the spray nozzle. Finally, it would be important to carry out a visual observation of the fuel spray cone in order to determine the atomization stage - film or filmless - since the generalization of the experimental data must be accomplished in dependence on the atomization stage. The experimental installation (Fig. 1) was constructed with consideration of the foregoing.

The stand was set up in a two-story enclosure. The part of the stand on the upper floor was covered with plexiglas. The spray nozzles being tested were mounted at the top of the chamber in vertical position, thus ensuring the symmetricity of the atomized stream. The inside

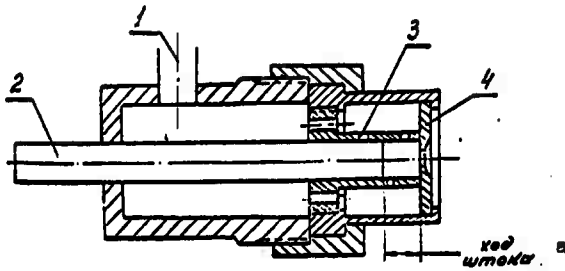


Fig. 2. Diagram of fuel spray nozzle: 1) Supply of fuel; 2) movable rod; 3) beaker with tangential orifices; 4) nozzle; a) Rod travel.

of the chamber was fitted out with a moving frame which could move over the entire height of the chamber by means of a system of block and tackle and winches, remaining in horizontal position the entire time. The frame was set up so that it was possible to mount on it: an annular collector for determination of spray density at various points in the transverse cross section of the stream, a sector collector for the determination of the degree of nonuniformity (asymmetry) of fuel distribution over the various sectors, and a device to trap the droplets of fuel on smoked plates.

By means of the above-enumerated devices it was possible to measure the volume of the atomized stream at any point. The annular and sector collectors were mounted on carriages generally situated to the side on brackets, from which each of these could be rolled onto the moving frame.

Above the chamber there was a bypass tube with a funnel and this device was mounted either in the center of the chamber, directly beneath the spray nozzle, picking up the entire stream, or it was positioned outside of the field of the atomized stream. By means of a three-way stopper the fuel was directed from the bypass tube either into a fuel tank or onto scales.

To prevent the deposition of fuel dust on the plexiglas walls cur-

tains of air were formed on the inside of the chamber by means of an exhaust fan. The stream of air into the chamber did not disrupt the development of the atomized stream from the spray nozzle and provided for conditions favorable to the visual observation of the atomization

The experimentally regulated spray nozzles whose diagrams are shown in Fig. 2 were tested on the experimental installation. As was pointed out earlier, all of the experiments were carried out with solar oil whose viscosity was varied by means of heating.

The quality of atomization was determined by measuring the number of impressions from the droplets dropped on the plates covered with a solar-oil soot. To produce a soot layer that was 0.5-0.7 mm thick, the plates were subjected to the soot deposition for a period of 30 minutes.

The soot-coated plates were attached to a rod which was in a non-moving position inside the slotted shutter. By varying the width of the slot it was possible to alter the exposure time which was selected so as to produce clear images.* The plates with the impressions [images] of the droplets were then placed on the object stage of the "Mir-12" measuring microscope, magnification 15 x. The microscope measuring error, according to the manufacturer's specifications, is determined by means of the formula

$$\Delta d_k = \pm \left(5 + \frac{d_k}{10} \right),$$

where d_k is the droplet diameter, in μ .

The soot-coated area with the droplets that was visible in the field of view of the microscope was illuminated by means of a reflector. A change in the angle of inclination for the rays incident from above on the plate from the reflector, it is possible to produce an image of the droplet impressions in great relief. With successive advance of the object stage beneath the microscope, the diameters of the

droplets were measured in circles of radii of 3.5, 5 and 7.5 mm. The transverse cross section of the atomized cone was broken down into concentric rings. The quality of atomization on an area of 78 mm^2 was measured once in each ring. In the compilation of the tables for the droplet dimensions, these were broken down into groups separated by intervals of 10μ .

The geometric characteristic $A = \frac{\pi \cdot R_f \cdot r_g}{f_{vkh}}$ for the spray nozzles ranged from 0.946 to 18.85 (R_f is the radius of the swirl chamber; r_g is the radius of the nozzle; f_{vkh} is the area of the inlet orifices). This was achieved by changing the area of the tangential channels through displacement of the rod. The diameters of the discharge orifices were 3.5 and 7 mm for the 8r and 5r spray nozzles, respectively. The radii for the respective swirl chambers were 4.3 and 13.1 mm. The area of the tangential channels at the inlet to the 8r spray nozzle was changed from 1.49 to 25 mm^2 and for the 5r spray nozzle this area was 7.63 mm^2 .

The following quantities were determined during the course of the experiment: the fuel flow rate B (kg/hr); the fuel pressure P (kg/cm²) ahead of the spray nozzles; the fuel temperature t_t (°C) by means of which the viscosity ν (cm²/sec) was determined; the density of the spray at a distance of 440 mm from the spray nozzle and the diameters of the droplet impressions. The method utilized in treating the experimental data is presented below. All of the experiments that have been carried out pertain to the filmless stage of atomization.

Among the shortcomings of the method utilized to measure the quality of atomization by trapping droplets of coated plates, as was pointed out earlier, we should include the circumstance that from among the many droplets in the stream it is only a small fraction of the drop that is measured. In order to obtain a picture most completely reflecting the phenomenon occurring throughout the entire stream, we

carried out measurement operations at 12 points along the radius of the stream. There arises the question as to which criterion characterizes the correct measurement at any given point?

The number of measured droplets at a given point was held to be adequate if the frequency curve of atomization constructed on the basis of these drops turned out to be smooth. In this case, the mean drop diameter was calculated from the formula

$$d_{sp} = \frac{\sum n_i \cdot d_i^3}{\sum n_i \cdot d_i^2}$$

and it turned out that the mean drop diameter determined from the total atomization curve was of the same order of magnitude. In those cases in which the frequency curve was irregular in shape, which was found to be the case with coarse atomization, the divergence between the indicated methods of calculating the mean drop diameter was considerable. However, through an increase in the number of measured impressions it was possible during the course of the experiment to achieve a satisfactory frequency curve of droplet distribution through the stream with respect to the various dimensions.

The frequency and the total curves characterizing the quality of atomization at a given point (in the ring) were plotted on the basis of the primary measurements. Then, with consideration of the distribution curve for the spray density, the frequency and total atomization curves for the stream as a whole were plotted. The mean stream-drop diameter d_k was defined as the abscissa of that point on the total atomization curve for which the ordinate is $R = 36.8\%$ [5]. The values of the mean drop diameter for the stream derived in this manner are presented in the table.

The method utilized to process the experimental data made it possible significantly to reduce the work involved in carrying out the mea-

Experimental Parameters and Results of d_k Calculations

Параметры опытов и результаты расчета d_k																					
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19			
Шифр форсунок	Диаметр отверстия источника d_0 , мм	Радиус вихревой камеры R , мм	Ход штока S , мм	Площадь в повороте f_{vkh} , мм ²	Геометрич. характеристика форсунок $A = \frac{\pi R r_f}{f_{vkh}}$	Модуль расхода $\frac{B}{\sqrt{P}}$	Давление перед форсункой P , атм	Температура топлива t , °C	Производит. форсунок B_t , кг/час	Площадь эквивалентного отверстия F_e , мм ²	Диаметр эквивалентного отверстия $d_e = \sqrt{\frac{4F_e}{\pi}}$, мм	Эквивалентная скорость $V_e = \sqrt{\frac{2P}{\rho}}$, м/сек	Число Рейнольдса $R = 10 V_e d_e / \nu$	Средний диаметр капля \bar{d}_k , мм	$\frac{d_k}{d_e} \cdot 100\%$	Наибольш. измерен. диаметр отдельной капли $d_{k \max}$, мм	$d'_{k \max} = \frac{d_{k \max}}{d_k} \cdot 100\%$				
5p	7	13.1	4	7.63	18.35	187	5.3	8	432	3.96	2.23	34.3	0.34	2280	490	0.217	432	390	-18.8		
...	7	13.1	4	7.63	18.85	187	10	8	21.5	3.96	2.23	47.1	0.196	3460	200	—	271	500	-0.74		
...	7	13.1	4	7.63	18.85	187	20	20	832	3.96	2.23	66.5	0.192	7780	—	—	210	560	328	-0.85	
...	7	13.1	4	7.63	18.85	187	40	22	1025	3.96	2.23	81.8	0.192	9580	—	—	131	550	273	-20.6	
...	7	13.1	4	7.63	18.85	187	60	22	1183	3.96	2.23	94.2	0.192	11930	230	—	107	470	219	-31.1	
...	7	13.1	4	7.63	18.85	187	80	22	1322	3.96	2.23	105.5	0.192	12350	—	—	158	450	229	-44.8	
...	3.5	4.3	4	9.95	2.37	105	20	8.5	470	2.23	1.635	66.5	0.36	3100	270	0.16	376	222	550	526	-18.1
...	3.5	4.3	4	9.95	2.37	105	10	8	332	2.23	1.635	47.1	0.34	2320	385	—	327	655	385	-18.0	
...	3.5	4.3	4	9.95	2.37	105	5	8	235	2.23	1.635	33.1	0.34	1640	445	0.24	405	860	175	-17.3	
...	3.5	4.3	3	3.5	0.76	55	10	20	174	1.17	1.22	47.1	0.20	3820	245	0.19	298	400	284	-15.0	
...	3.5	4.3	3	9.95	2.37	105	10	25	332	2.23	1.635	47.1	0.183	4860	—	—	330	198	198	-10.5	
...	3.5	4.3	6	17.8	1.33	148	10	25	408	3.14	2.60	47.1	0.183	3750	250	0.125	238	360	213	+0.6	
...	3.5	4.3	8	25	0.946	169	10	25	634	3.58	2.40	47.1	0.183	6120	230	0.1195	238	300	178	+24.9	
...	3.5	4.3	4	9.95	2.37	105	30	23	745	2.23	1.635	105.5	0.173	16250	100	0.0695	117.5	160	113	-3.83	
...	3.5	4.3	4	9.95	2.37	105	40	31	832	2.23	1.635	81.8	0.075	18250	102.8	0.06	160.8	160	113	-12.2	
...	3.5	4.3	4	9.95	2.37	105	5	49	235	2.23	1.635	33.1	0.075	7440	154	0.0914	108	—	—	—	
...	3.5	4.3	4	9.95	2.37	105	5	66	235	2.23	1.635	33.1	0.049	11400	117	0.0395	121	—	—	—	
...	3.5	4.3	1	1.49	15.85	28.3	30	61	155	0.3	0.67	81.8	0.035	12750	89	0.0378	60.8	140	83	-36.5	
...	3.5	4.3	3	3.5	0.75	55	5	31	129	1.17	1.22	33.1	0.128	3150	—	—	197.4	380	225	-14.0	
...	3.5	4.3	3	3.5	0.75	55	20	31	248	1.17	1.22	66.5	0.138	6340	—	—	151.6	350	198	-19.0	
...	3.5	4.3	3	9.95	2.37	105	80	29	428	1.17	1.22	115.5	0.138	10220	—	—	85	230	118	-21.3	
...	3.5	4.3	4	9.95	2.37	105	8	29	297	1.17	1.685	42.0	0.138	6130	—	—	209	810	184	+12.0	

- 1) Spray-nozzle designation;
- 2) discharge orifice diameter d_s , in mm;
- 3) radius R of swirl chamber, in mm;
- 4) rod travel S , in mm;
- 5) inlet area f_{vkh} , in mm²;
- 6) geometric characteristics of the spray nozzle, $A = Rr_s/f_{vkh}$;
- 7) absolute value of flow rate B_r/\sqrt{P} ;
- 8) pressure P ahead of the spray nozzle, in atm;
- 9) fuel temperature t , °C;
- 10) spray-nozzle capacity B_t , in kg/hr;
- 11) area F_e of equivalent orifice, in mm²;
- 12) diameter of equivalent orifice, $d_e = \sqrt{4F_e/\pi}$, in mm;
- 13) equivalent velocity $V_e = \sqrt{2P/\rho}$, in m/sec;
- 14) fuel viscosity ν , in cm²/sec;
- 15) Reynolds number $R = 10 V_e d_e / \nu$;
- 16) mean droplet diameter \bar{d}_k , in mm;
- 17) $\bar{d}_{k1} = d_e \cdot (18.3/R e)^{0.59}$, in μ ;
- 18) greatest measured diameter $d_{k \max}$ of an individual drop, in mm;
- 19) d'_k from the expression $0.2 = 100e^{-(d_{k \max}/d_k)^n}$.

surements. In particular, this method is suitable for the determination of atomization quality from spray nozzles of high capacity (and, consequently, of coarse atomization). Since it is difficult for such spray

nozzles to obtain a properly shaped total distribution curve, we can employ a simplified method of plotting these distribution curves. In addition to the distribution curves in the small-drop region which, as was demonstrated by experiment, is always smooth, we must also measure the diameter of the largest drop in the stream. The curve for the region of the small drops and the diameter of the largest drop determine the nature of the entire curve as a whole, since the measured drops yield the direction of the distribution line in the coordinate grid $\lg \lg R = f(\lg d_{\text{L}})$, while the value of the maximum drop yields its length.

The primary experimental data on the measurements of atomization quality (B , P , v and \bar{d}_k) presented in the table were processed by means of a criterial equation valid for the filmless stage of disintegration:

$$\frac{\bar{d}_k}{d_e} = f(Re_e). \quad (2)$$

The equivalent spray-nozzle diameter which we have taken as the characteristic linear dimension is calculated by means of the formula

$$d_e = \sqrt[3]{\frac{4F_e}{\pi}}, \text{ mm}. \quad (3)$$

The area of the equivalent orifice was determined from the expression $B = 3.6 F_e = \sqrt{20gP\gamma_t}$, where γ_t is the specific weight of the fuel in g/cm^3 ; B is the fuel flow rate, in kg/hr ; P is the pressure ahead of the spray nozzle, in kg/cm^2 .

$$F_e = \frac{B}{3.6\sqrt{20gP\gamma_t}}, \text{ mm}^3. \quad (4)$$

With consideration of the units involved, the Reynolds number for the equivalent orifice is equal to

$$Re_e = \frac{10 \cdot v_e \cdot d_e}{\nu}, \quad (5)$$

where v_e is the velocity in the equivalent orifice, in m/sec . It is equal to

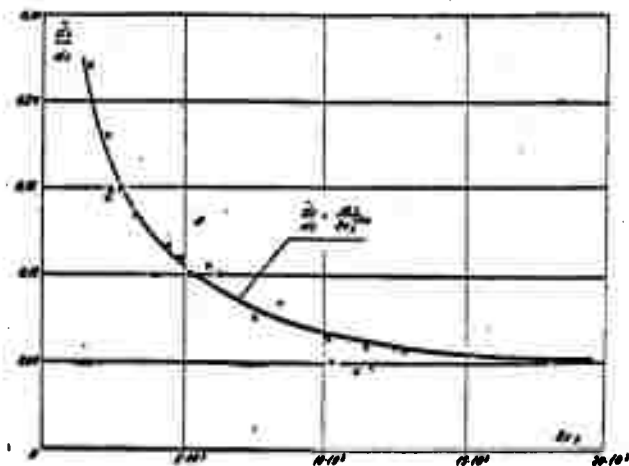


Fig. 3. Function $\bar{d}_k/d_e = f(Re_e)$.

$$v_s = \sqrt{20g \cdot \frac{P}{\gamma}}. \quad (6)$$

The derived experimental data fall satisfactorily onto a single curve (Fig. 3) whose equation has the form:

$$\frac{\bar{d}_k}{d_e} = \frac{18.8}{Re_e^{0.56}}. \quad (7)$$

The parameters in the experiment varied in the following range: the pressure ahead of the spray nozzle varied from 5 to 60 kg/cm²; the kinematic viscosity ranged from 0.04 to 0.4 cm²/sec; the fuel flow rate ranged from 123 to 1322 kg/hr; and the Reynolds number varied from 1640 to 18,280.

In processing the experimental data for the 8r spray nozzle, these data derived for various lengths of rod travel and for various values of fuel pressure and viscosity, we noted the constant inclination of the total atomization curves (Fig. 4), which indicates the constancy of n for all operating regimes of this spray nozzle ($n = 3.6$). For the 5r spray nozzle we obtained in an analogous manner $n = 3.0$ (Fig. 5). Since the quantities R_f and r_g remained constant for each of these spray



Fig. 4. Total curves of atomization for the 8r spray nozzles in coordinates

$$\lg \left(\lg \frac{100}{R} \right) = f(\lg d_i).$$

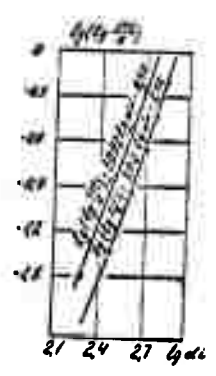


Fig. 5. Total curves of atomization for the 5r spray nozzles in coordinates

$$\lg \left(\lg \frac{100}{R} \right) = f(\lg d_i).$$

nozzles, it may be assumed that there exists the relationship $n = f\left(\frac{R_p}{r_s}\right)$. An analysis of the experimental data [3] confirms this assumption. Thus, for the group of spray nozzles for which $5.5 > R_p/r_s > 3.3$ the quantity n was equal to 2.5, while for the spray nozzles for which $10 > \frac{R_p}{r_s} > 6.2$, it is equal to 2. The value of n as a function of R_p/r_s is shown in Fig. 6. It is possible to determine the experimental quantity characterizing the nonuniformity of drop dimensions in the stream on the basis of this function.

The literature [3, 4, 5] contains references to the effect that the quantity n ranges from 2 to 4. Approximately the same values for the quantity n are given in Fig. 6.

In approximate terms the function $n = f(R_p/r_s)$ may be represented as the straight-line equation

$$n = 4.42 - 0.42 \frac{R_p}{r_s}. \tag{8}$$

The quantities \bar{d}_k and n completely characterize the quality of atomization for fuel by means of centrifugal spray nozzles for the filmless stage of decay on injection into nonmoving air under atmospheric pressure and at room temperature.

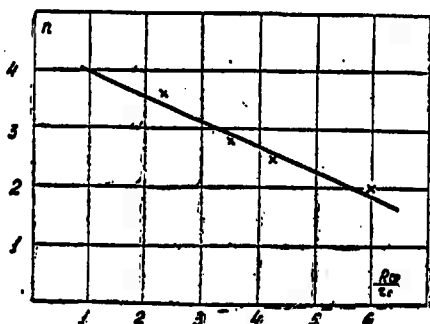


Fig. 6. Function $n = f(R_p/r_s)$.

Later on we will indicate yet another simple means of achieving an approximate evaluation of atomization quality requiring no extensive expenditure of labor in the processing of the experimental data. The essence of this method lies in the fact that if we know the magnitude of d in Expression (1) and if we know the diameter of only the largest of the drops ($d_{k_{max}}$), it is possible to calculate the mean diameter \bar{d}_k of the atomized drop by solving Eq. (1) for \bar{d}_k . In this case, we assume that 99.8% of all the drops in the stream have a diameter smaller than $d_{k_{max}}$.

The values of the mean drop diameter, calculated roughly by this approximate method, are presented in the table.

CONCLUSION

The fuel-atomization quality achieved by means of centrifugal spray nozzles of high capacity has been determined experimentally. It has been demonstrated that the Reynolds number computed in accordance with the equivalent orifice satisfactorily reflects the conditions of

stream fragmentation for the filmless stage of the disintegration in the injection of the stream into nonmoving air at room temperature and under atmospheric pressure. In calculating the atomization quality in accordance with the proposed formula (7) we must know two quantities: the fuel flow rate and the pressure. These quantities are easily determined experimentally. The given calculations may be utilized for a comparative evaluation of spray-nozzle operation, in calculating the rate and efficiencies of vaporization for polydispersed streams of fuel, etc.

FROM THE EDITORS

Experimental material on the determination of liquid-atomization characteristics has recently been treated in terms of criteria derived on the basis of the theory of similarity (see B.V. Raushenbakh [et al] "Physical Fundamentals of the Working Cycle in the Combustion Chambers of Air-Reaction Engines." Moscow, 1964). Yu.I. Khavkin adopted another method for the processing of the experimental material; however, his data are of interest not only from the standpoint of experimental material on high-capacity spray nozzles, but also from the standpoint of material sufficient for processing in the criteria of similarity.

The data presented in this paper serve as confirmation of the method proposed by the Kazakh Scientific Research Institute of Power Engineering for the evaluation of liquid atomization quality based on the drop of the largest diameter (see the article by S.I. Ofitserov "On the Evaluation of the Dispersion of an Atomized Liquid." "Problems of Thermal Power Engineering and Applied Thermal Physics," Issue 2, Alma-Ata, 1965).

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[Footnotes]

- 1 The Leningrad "Economizer" Plant.
- 5 On full aperture opening the oscillograph-measured exposure [opening] of the shutter came to 1/50 sec.

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[Transliterated Symbols]

- 2 $\kappa = k = \text{kapel}' = \text{drop}$
- 6 $\dot{\Phi} = f = \text{forsunka} = \text{spray nozzle}$
- 6 $c = s = \text{soplo} = \text{nozzle}$
- 6 $\text{vx} = \text{vkh} = \text{vkhodnoy} = \text{inlet}$
- 6 $r = t = \text{toplivo} = \text{fuel}$
- 7 $\text{cp} = \text{sr} = \text{sredniy} = \text{mean}$
- 9 $\text{э} = e = \text{ekvivalentnyy} = \text{equivalent}$