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TRANSLATION

ATOMIZATION OF A LIQUID IN A SUPERSONIC FLOW

By

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FOREIGN TECHNOLOGY DIVISION

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ATOMIZATION OF A LIQUID IN A SUPERSONIC FLOW

M. S. Volynskiy

The atomization [1] and combustion of a fuel in a supersonic flow is of interest in air-breathing jet engines with the flow in the combustion chambers at M 1.

In work [2] it is proposed that the combustion of the prepared mixture be accomplished in a stabilized detonational wave. The development of the process of combustion in a high temperature supersonic flow is determined by the quality of the fuel atomization, in the engine atomization, evaporation, and mixing.

Below are presented the results of a study of the form of the torch of atomization and also the scale of the atomization in a supersonic flow is presented. An examination of the process of atomization is conducted within the frame work of an aerodynamically posed problem without a computation of the heat transfer and phase transitions (evaporation, dissociation etc.)

It is assumed that disintegration of the liquid occurs very rapidly and the heat phenomena (in a number of cases do not succeed in influencing substantially the initial diameter of the particles (which later on, of course, are subject to evaporation).

Symbols

a -- diameter of drop;

a_m a_{max} -- are median and maximum diameter of the drops in the spectrum of atomization;

τ -- time;

ε -- level of turbulence in the gas flow;

C_x -- drag coefficient of drop

R_o -- Reynolds number at the initial moment of a flow around a drop

ρ_1, ρ_2 -- density of gas and liquid

ν_1, ν_2 -- kinematic viscosity of gas and liquid

β_o -- initial angle of drop's departure from nozzle of atomizer

x, y -- absolute coordinates

l -- relative coordinate

γ -- angle of inclination with respect to the trajectory of drop to the axis ox

Y, L -- coordinates of the asymptote in an absolute and a relative system.

d -- diameter of nozzle of direct-spray

m, F -- mass and area of middle cross-section of the drop

σ -- surface tension of the liquid

T_o, P_o -- temperature and pressure of deceleration

ΔP -- drop in pressure on injection of the liquid.

a_* -- speed of sound in gas

n -- number of drops measured in the experiment

$Y_э$ -- experimental value of ordinate of asymptote

φ -- coefficient of torch of atomization

R -- Reynolds number of flow around drop

M -- Mach number of flow

D -- Weber number

1. A model of the phenomenon and the asymptote of the torch of atomization. Atomization in a flow of supersonic speeds with an injection of liquid from a cylindrical aperture at an angle of 90° to the axis of flow [3] is distinguished by the following peculiarities.

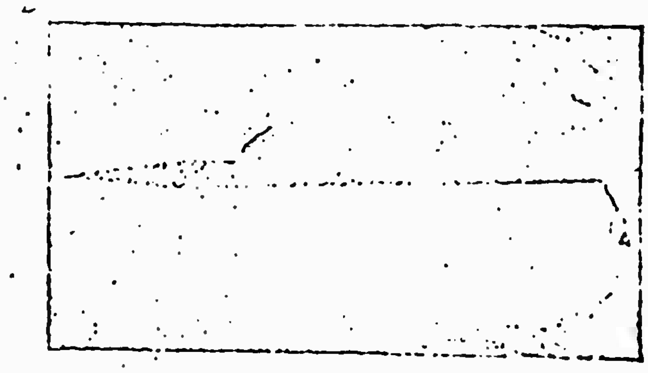
1. The stream disintegrates near the place of injection, however a small section of disintegration exists at the base of the stream in the form of a "liquid leg". The depth of penetration of the torch of atomization into the flow is noticeably less than in subsonic flows (fig. 1).

2. In front of the torch appears a curvilinear shock wave (fig. 1). its element adjoining to the base of the stream, is nearly a normal shock.[1]

1. Sometimes in this zone is observed a small shaped or a detached sloping shock wave, apparently as the result of the interaction between the wave and the boundary layer on the atomizer.

The steepness of initial section of the shock wave rapidly diminishes, and the wave approximates a rectilinear characteristic, corresponding to the Mach number of incident flow.

3. The outer limit of the torch is sharply outlined and tends to a horizontal asymptote, with which it nearly joins. Farther on the limit disappears as the result of turbulent diffusion of the drops.



GRAPHIC NOT REPRODUCIBLE

Fig. 1

An investigation by the photographic spark method, methcd of Toepler, ect. make it possible to present a model of the atomization and the motion of particles in the torch. The process of atomization, in the general case, is composed, apparently, of two stages. The nonatomized stage of the stream is deformed i.. a thin film, which is disintegrated in zone after the normal shock, i.e. in the subsonic flow. Then, the second stage ensues. The drops will pass through the zone of supersonic flow back of a curvilinear wave, where the impact pressure of the gas increases, here the drops can split into smaller drops.

The subsequent displacement of the particles in the torch can be represented as the main motion along a system of stationary (averaged) trajectories and the dispersion of droplets with respect to these trajectories as the result of perturbations in process of the disintegration of the stream and turbulent diffusion. A swarm with a high particle density, moves within the torch.

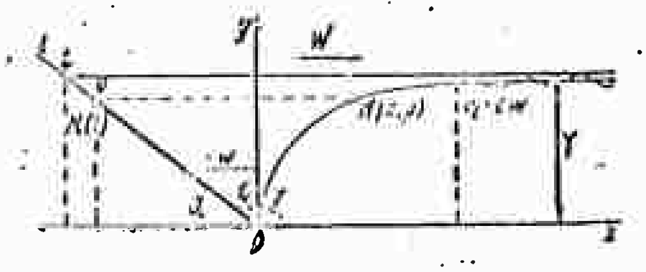


Fig. 2

However, along the limits of the torch, its density sharply drops (distribution curve of concentrations in fuel torches is characteriszed by a sharp maximum within and steep fall towards the periphery).

As a first approximation we shall assume that the drops at the outer limit of the torch almost everywhere move as individual particles in a gas with parameters, close to parameters of the incident flow. The swarm of drops will not change the flow before the torch in the zone of supersonic flow (perturbations will not be transmitted along the flow) which is possible in subsonic processes.

Let us suppose the outer limit (which ordinary photographs second) as the stationary trajectory of the largest drop a_{max} in the spectra of atomizatior.

Let us examine the problem about the asymptote of the limit, formed by the trajectory of a drop a_{max} in the vertical plane of symmetry of the torch. We shall select the orgin as it was shown in Fig. 2.

The equation of the motion of a nonevaporating spherical drop having a diameter $\underline{a}$, a mass $\underline{m}$ has the form

$$m\frac{dv}{d\tau} = u^\circ c_x f \frac{\rho_1 u^2}{2} \qquad \left(m = \rho_1 \frac{\pi a^3}{6},\ f = \frac{\pi a^2}{2}\right) \qquad (1.1)$$

$$v = u + w \qquad (1.2)$$

Here τ is the time, v --the absolute velocity of the drop, u is the relative velocity of the drop, u is the unit vector of the relative velocity of drop, v_o is exhaust velocity.

The drag coefficient C_x of a spherical drop will be in the general case a function of the Reynolds number and Mach number of the flow around the drop.

However an investigation of motion of a particle after a shock wave in a field of variable speed and density, shows that in the relative motion, the drop is blown around by the subsonic flow [3]. Consequently, it is possible to ignore the influence of the reach number on C_x. The experimental relation $C_x = C_x(R)$, given by V. A. Olevskiy [4] for a sphere and also valid in a fairly wide range of Reynolds numbers R, has the form

$$C_x = A_1 + \frac{A_2}{\sqrt{R}} + \frac{A_3}{R} = 0.32 + \frac{4.4}{\sqrt{R}} + \frac{24}{R} \quad (10^{-3} < R < 6\cdot 10^{3}) \qquad (1.3)$$

The trajectory of a drop with a diameter, a, moving with an initial speed v_0 at an initial angle $\beta_0 = 90°$ to the axis of flow of gas of parameters w, ρ_1, ν_1, has a horizontal asymptote with the ordinate Y.

For determining Y, let us turn to the relative system of coordinates, associated with the incident flow (in which, as is well known, the trajectory of a drop with w = const becomes a straight line).

Equation (1.1) after eliminating τ assumes in new coordinates the following form (fig. 2):

$$\frac{du}{dl} = -\frac{3}{4}\frac{\rho_1}{\rho_2}\frac{C_x}{a}u \qquad (1.4)$$

Formula of the co-ordinate conversion.

$$x = l\cos\gamma + w\tau, \qquad y = l\sin\gamma = l\frac{v_0}{u_0} \qquad (1.5)$$

A drop in a relative system monotonically tends to a certain asymptotic point M_1 (L). By substituting into the equations of motion (1.4) the drag coefficient from formula (1.3), after simple transformations we obtain

$$\frac{du}{dl} = -B\left(B_1 u + B_2 u^{1/2} + B_3\right) \qquad (1.6)$$

$$B = \frac{3}{4}\frac{\rho_1}{\rho_2}\frac{\nu_1}{a^2}, \quad B_1 = \frac{A_1 a}{\nu_1}, \quad B_2 = \frac{A_2 a^{1/2}}{\nu_1^{1/2}}, \quad B_3 = A_3 \qquad (1.7)$$

The boundary condition $u = u_0$ at $l = 0$.

Integrating within the limits $u_0 \geq u \geqslant 0$ from the beginning of the motion to the complete entrapment, we write as

$$L = -\frac{1}{B}\int_{u_0}^{0} \frac{du}{B_1 u + B_2 u^{1/2} + B_3} \tag{1.8}$$

The complete entrapment of drop (when its speed is compared with speed of the flow) will be attained at infinity.

In a turbulent flow it is possible to assume a drop entrapped from the moment, when its relative velocity u_ε becomes successively equal to the pulsational speed (ε is the level of turbulence). Up to this moment usually we ignore the effect of turbulence (if energy of the pulsations are small in comparison with the energy of the mean motion).

Thus, the integral (1.8) for a real motion should be computed from u_0 to $\varepsilon\omega$. However, in flows of moderate or small turbulence, the value of $\varepsilon\omega$ is comparatively small ($\varepsilon = 0.05$), and the result therefore varies very little, if we compute the integral in the interval $[u_0, 0]$. From expression (1.8) it follows that an asymptote exists always, except in the particular and imaginary case of $A_2 = A_3 = 0$, corresponding to C_x = const in the entire interval of the motion. By computing integral (1.8), we obtain the abscissa of the asymptotic point, to which the drop tends in a relative motion.

$$L = \frac{1}{2CC_1}\left(\ln\frac{C_1 + C_2 + C_3}{C_1} - \frac{C_2}{\sqrt{\Delta}}\operatorname{arctg}\frac{2C_1\sqrt{\Delta}}{\Delta + 2C_1C_2 + C_2^2}\right) \tag{1.9}$$

$$C_1 = A_1 R_0, \quad C_2 = A_2\sqrt{R_0}, \quad C_3 = A_3, \quad C = \frac{3}{8}\frac{\rho_1}{\rho_2}\frac{1}{R_0}$$

$$\Delta = 4C_1C_3 - C_2^2 > 0 \tag{1.10}$$

Here $R_0 = u_0\, a/\nu_1$ -- the initial Reynolds number, ν_1 -- kinematic viscosity of the gas. Using the co-ordinate conversion (1.5), we find the ordinate.

$$Y = 4.17\,\frac{\nu_0}{u_0}\frac{\rho_2}{\rho_1}\,a\left(\ln\frac{C_1 + C_2 + C_3}{C_1} - \frac{C_2}{\sqrt{\Delta}}\operatorname{arctg}\frac{2C_1\sqrt{\Delta}}{\Delta + 2C_1C_2 + C_2^2}\right) =$$

$$= 4.17\,\frac{\nu_0\rho_2}{u_0\rho_1}\,a\Phi(R_0) \tag{1.11}$$

Formula (1.11) expresses the ordinate of the asymptote of the torch in a flow of moderate turbulence by the parameters of the gas, the flowing liquid and the size of the drops $a \sim a_{max}$. At present it is impossible to compute Y, from formula (1.11) because the size of the drops is unknown. We shall introduce an experimental relationship, determining the ordinate of the asymptote of the torch Y.

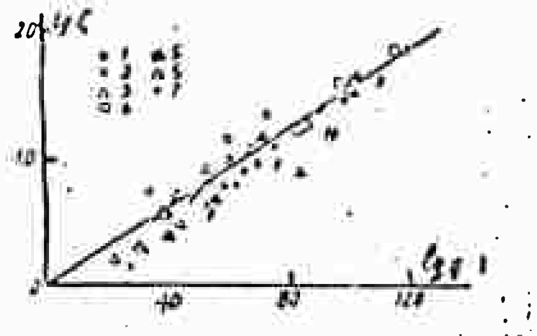


Fig. 3

The processing of photographs of torches of atomization in a supersonic flow makes it possible to obtain the fairly general relationship (Fig. 3)

$$\zeta = 0.15\eta \qquad \zeta = \frac{Y_0}{d}\left(\frac{w}{a_*}\right)^{-1/6} \qquad (1.12)$$

$$\eta = \left(\frac{\rho_2 v_0^2}{\rho_1 w^2}\right)^{1/2}\left(\frac{wd}{\nu_1}\right)^{1/6}\left(\frac{\rho_1 w d}{\sigma}\right)^{-1/6}$$

Here d is the diameter of nozzle aperture of atomizer, σ — surface tension of the liquid, a_* is the speed of sound in gas.

The dimensionless ordinate of the asymptote of torch increases with an increase of the relation between kinetic energies of injected liquid and gas, Reynolds and Mach numbers of the flow and decreases with an increase of Weber's criterion (which conforms with the physical meaning of the criteria). The Mach number M, diameter d, temperature T_0 that and the pressure P_0 in the deceleration of the flow the fall of pressures in the fuel feed ΔP varies within the limits

$$1 < M < 2.8, \quad 0.4 \leqslant d \leqslant 4.5 \text{ мм}, \quad 2.5 \leqslant P_0 \leqslant 16 \text{ ama},$$
$$250 \leqslant T_0 \leqslant 550°\text{K}, \quad 5 \leqslant \Delta P \leqslant 45 \text{ amu}$$

2. The scale of the atomization in a supersonic flow. Literature on the scale of atomization in a supersonic flow (due to difficulties of experimental investigation) is sparse. Here it is possible to indicate results Bitron [1]. for atomizers of very small consumptions.

In the experiment described below was used (after certain improvements) the well-known method of collecting drops on a layer of carbon, covered by the vapors of burnt magnesium (MgO).

The layer was applied to the flat of a special rod (closed cylindrical case with a slot), placed along the cross-section diameter of the flow. During measurement in the flow the case is moved along the rod, as it provides access for the drops to the collecting surface through the slot in the case.

Experiments were made in an installation, where into a free jet of supersonic speeds, were fed alcohol and water from atomizers with various diameters of the nozzle aperture d. The air from main line of high pressure passed through receiver to the supersonic nozzle. The rated conditions of the effusion with the number M = 1.0, 1.2, 1.8, 2.4 were realized by means of interchangeable dynamic nozzles.

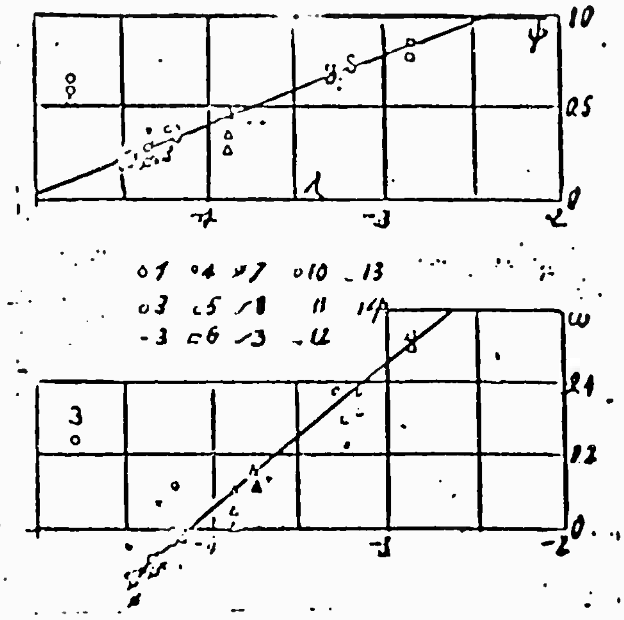


Fig. 4

Parameters of the flow were established and were controlled by measurement of full pressure p_0 in the receiver, temperature T_0 (thermocouple) and static pressure at the discharge section of the nozzles (mercury U-shaped manometer). Photographs of the gas jet on output made according to Toepler's method were an additional control of the method.

In most cases fuel was fed from the center of the flow, and in a series of experiments the jet of alcohol flowed out from the aperture on the wall of the nozzle or from pipe on periphery of the jet.

$$P_0 = 1.9 \div 5.6\ ama, \quad T_0 \approx 275°K, \quad \Delta P = 5 \div 45\ amu$$

Additionally a small number of experiments was made in evaluating the effect of a normal shock wave on the size of the drops. For this purpose the torch with an already known spectrum of atomization was passed across the surface of the detached shock wave before shell, beyond which the measurement of the scale of the atomization was made.

The drops were collected at a certain distance from the point of injection, where the speed of the flow diminishes to 60-80 m/sec.

The layer of carbon had a thickness of 0.5 to 0.6 mm. This made it possible to ignore the difference between the imprints of the drops and their actual dimensions. In our experiments it was found possible to ignore the evaporability of the drops.

The diameters of imprints were measured under a microscope (usually about 1000 measurements per handling). The average error of measurements amounted to ± 2 to ± 4 MK.

Spectra curves making it possible to find the median diameter a_m and maximum a_{max}, corresponding to 95 % of the mass of the drops (see table). The letters a, b, c, ... indicate method of injecting the liquid into the flow according to a procedure , but the figure in the column "of the designation", --

-- experimental points in Fig. 4.

In order to facilitate the seeking of the form of dependencey for a_{max}, the factor of dimension we associate with any magnitude, more admissable to experimental determination.

As such we shall select the ordinate of asymptote of the atomization torch Y_0.

In using the adopted model (§ 1), where the outer limit of the torch is compared to the trajectory of the largest drop, we shall compare experimental values Y_0 from formula (1.12) with the computed magnitude of $Y(a_{max})$ from relationship (1.11)

$$Y_0 = \varphi Y(a_{max}) \tag{2.1}$$

If we solve this expression with respect to a_{max}, we shall obtain the relationship for maximum diameter of the drops. The variable factor φ we shall designate as the coefficient of the torch of atomization. It expresses the total effect of factors, explicitly ignored in the adopted scheme of the phenomenon. These factors include the substitution of the complex velocity profile and density after the shock wave of the torch by parameters p_1, w, the ignoring of the length "of the liquid leg" at the base of the fuel stream, the substitutions of the swarm of particles by a single drop etc. According to the physical meaning of these factors, $\varphi > 1$ and the greater it differs from unity, the larger the indicated effects (tendency of the effect which is identical). According to (2.1) we write out

$$0.15\left(\frac{\rho_1 v^2}{\rho_1 w^2}\right)^{1/6}\left(\frac{u_0 d}{\nu_1}\right)^{1/6}\left(\frac{w}{c_0}\right)^{1/6}\left(\frac{\rho_1 u_0^2 d}{\sigma}\right)^{-1/6} = \varphi \cdot 4.17\,\frac{\rho_2 v_0}{\rho_1 u_0}\,a_{max}\Phi(R_{max}) \quad (2.2) \tag{2.2}$$

The function

$$\Phi(R_{max}) \text{ or } R_{max} = \frac{a_{max} u_0}{\nu_1}$$

is transcendental this makes it impossible to solve equation (2.2) with respect to a_{max}.

a_M, мк	a_{max}, мк	ж	M	T, °K	p, ата 1	d, мм	Δp, ати 2	Жидкость 3	Способ подачи жидкости 4	Обозначения 5
6.5	12	1017	1.8	275	5.4	0.4	5	6 Спирт		1
7.5	13.5	1616					15			
8	16	1695					40			2
7	16	2325				1	15		a	
7.5	17	1931					40			3
9	17	2175				2	5			
11	18	1790					15			
5.7	14	1165	1.8	275	5.4	1.1	5	6 Спирт		4
7.7	13.5	1026					15		b	
10.5	18	1923					40			
10	20	991	1.8	275	5.4	1	5	7 Вода		5
10	21	1168					15			
10	24	809					40			
13	26	2200				3	5	6 Спирт	c	6
14	31	1700					15			
13.5	31	1540				4	5			
15	36	1500					10			7
15	35	1252					12			
6	15	450	1	271	1.9		0.315	6 Спирт		8
7	16	470					40			
10	18	864				1	5			9
11	23	13[illegible]4					15		d	
13	28	1897				1	5	7 Вода		10
16	30	1199					15			
10	19	1443				0.4	5			
11.5	23	1317					15			11
16	30	880	1	271	1.9	1	5	7 Вода		12
13	29	773					15		e	
8	17	1373	1.2	272		1.1	5	6 Спирт		13
9	14	1046					15		f	
10.5	22	1858					40			
6	11	275	2.4	277	13	1	15	6 Спирт	g	14
8.5	16	537					40			

Results of an experimental investigation of the scale of atomization in a supersonic flow

1) ata; 2) ati; 3) liquid; 4) method of supplying of liquid; 5) Designation; 6) Alcohol; 7) Water.

We aproximate Φ by the power function

$$\Phi(R_{max}) \approx 0.28 R_{max}^{\gamma}, \quad 400 \leqslant R_{max} \leqslant 6000 \qquad (2.3)$$

After respective transformations, we obtain

$$\frac{a_{max}}{d} = \left(\frac{0.15}{4.17\cdot 0.25}\right)^{[illegible]} \left\{\frac{\rho_1}{\rho_2}\left[1 + \left(\frac{v}{w}\right)^2\right]\right\}^{[illegible]} \frac{R^{[illegible]} M^{[illegible]}}{D^{[illegible]} \varphi^{[illegible]}}, \quad D = \frac{\rho_1 w^2 d}{\sigma}, \quad R = \frac{dw}{v_1}. \qquad (2.4)$$

The coefficient of the torch φ we seek in the form of

$$\varphi \sim \frac{R^m}{D^n}, \qquad (2.5)$$

Here the constants m, n > 0; they are determined experimentally.

It is possible, for example, to assume that with a decrease in R, drag coefficient of the flow around the torch increases and, consequently, the aerodynamic forces, deforming and destroying "liquid leg". An increase of criterion D also reduces the initial zone of the disintegration of the liquid jet.

All the statements above facilitate the analysis of the structure of the formula for a_{max}. The experimental relationship being sought acquires the form

$$\Psi = 78\lambda^{[illegible]}, \quad \Psi = \frac{a_{max}}{d}\left(\frac{a_* d}{v_1}\right)^{[illegible]} \left(\frac{\rho_2}{\rho_1}\right)^{[illegible]} \left[1 + \left(\frac{v_0}{w}\right)^2\right]^{-[illegible]}, \quad \lambda = \frac{\sigma}{\rho_1 w^2 d} \qquad (2.6)$$

In Fig. 4 the results of processing of experimental data for a_{max} in coordinates of lg Ψ and lg λ are presented. It turns out that also the median diameter of spectrum a_m conforms with the analogous relationship

$$\omega = 45\lambda^{[illegible]}, \quad \omega = \frac{a_m}{d}\left(\frac{a_* d}{v_1}\right)^{[illegible]} \left(\frac{\rho_2}{\rho_1}\right)^{[illegible]} \left[1 + \left(\frac{v_0}{w}\right)^2\right]^{-[illegible]} \qquad (2.7)$$

The dimensionless parameter $a_* d/v_1$ appears as a ratio of the Reynolds number wd/V_1 to the Mach number w/a_*. The values w and d exert the greatest influence on the size of the drops. Formulas (2.6), (2.7) should be assumed as a first approximation, subject to further modification. They contain by far not all the criteria of the problem (number of which, according to the well-known "P- theorem", is equal to 8).

The complex v_2/v_1 does not enter into the formulas, apparently, the obtained relationships are valid for not very viscous liquids of the type water, alcohol, kerosene (at temperatures, close to those of the experiment or higher). The effect of the number M is found to be rather weak; this agrees with data of experiments made by Bitron [1], and it conforms to the weak effect of M on the asymptote of the atomization torch.

In Bitron's work the kinetic energy of a given liquid was very small in comparison with the energy of the gas flow. In this case it is impossible to speak of a well-developed torch of atomization, possessing ever so wide a marked range.

Thus, Bitron's data pertain to particular processes of atomization.

The order of magnitudes in the sizes of drops, obtained in Bitron's experiments, are comparatively close to the data cited herein, but the small values of diameter of nozzle aperture differ greatly from those given from its formula with an increase of d ($d \gtrsim 1.0 - 1.5$ mm).

The attempt by Bitron to use the well known Nikuyama -- Tanazava formula for a description of the results on the size in a supersonic atomization, apparently is insufficiently perspective. This formula was obtained for subsonic processes of flow, and besides, has a primary defect: namely the dimensional relationship, which does not possess sufficient generality.

More perspective is the attempt of generalizing formulas of a subsonic atomization with the introduction of parameters of flow after a normal shock (zone of the torch base).

In conclusion let us note that described experiments herein shows an abrupt decrease in the size of the drops during their passage through a shock wave (which agrees with comments available in literature).

Thus, for example, a torch with a spectrum $a_{max} = 16$ mk, $a_m = 7$ mk after passage through a shock with parameters of the incident flow $M = 1.8$, $T_o = 275$ K, $P_o = 5.4$ ata will have spectrum with $a_{max} = 8$ m and $a_m = 4$ m.

An oblique shock with a slope $\sim$ 40 to 50°, no longer exerts a marked effect on the size of the drops. In passing through a normal shock, a drop is subject to the effect of the pressure gradient, however the period of the reaction is very short (owing to the shallowness of the shock). Apparently, the generation of a great relative velocity during the fall of a drop into the zone after the shock, is more significiant.

Submitted Nov. 1962

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