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FOREIGN TECHNOLOGY DIVISION

METHOD OF CALCULATION OF GENERATOR CLEARANCE OF A LIQUID FUEL INJECTOR

By:

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METHOD OF CALCULATION OF GENERATOR CLEARANCE OF A LIQUID FUEL INJECTOR

BY: N. S. Lamekin, Eng.

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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.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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METHOD OF CALCULATION OF GENERATOR CLEARANCE OF A LIQUID FUEL INJECTOR

N. S. Lamekin, Eng.

(Moscow Aviation Institute)

In this work is considered the question on determination of the length of the first region of instability in a gas jet, flowing from a channel under conditions of underexpansion, for the purpose of obtaining recommendations for the magnitude of clearance in an ultrasonic generator of a low-differential injector.

The solution of the gas-dynamical problem is made in the assumption on the correctness of the equation of gas dynamics of a plane potential flow of gas for the case of flow in radial clearance.

Results are given of experiments on the study of the fineness of liquid atomization by an injector with an ultrasonic generator, conducted while taking into account recommendations of the author related to the length of the region of instability.

Swirl-type injectors operate at differential liquid pressures from 1 to 75 atm. For certain motors in the range of differential pressures up to 6 atm (gage), these injectors atomize the liquid unsatisfactorily, since the average diameter of the droplet reaches 300-500 μ. It is known that the complete process of combustion is observed when the average diameter of the droplet is ≤140 μ. Because of this, swirl-type injectors operate from differential pressures in

6 atm (gage), which limits their range of application.

For breaking up the liquid flowing from the injector at low pressures, it is possible to use ultrasonics. The source of ultrasonics in the given case is the gas generator 3 (Fig. 1). Under action of ultrasonic vibrations appearing in the generator 5 chamber, the liquid jet, flowing through clearance 4, is broken up into drops.

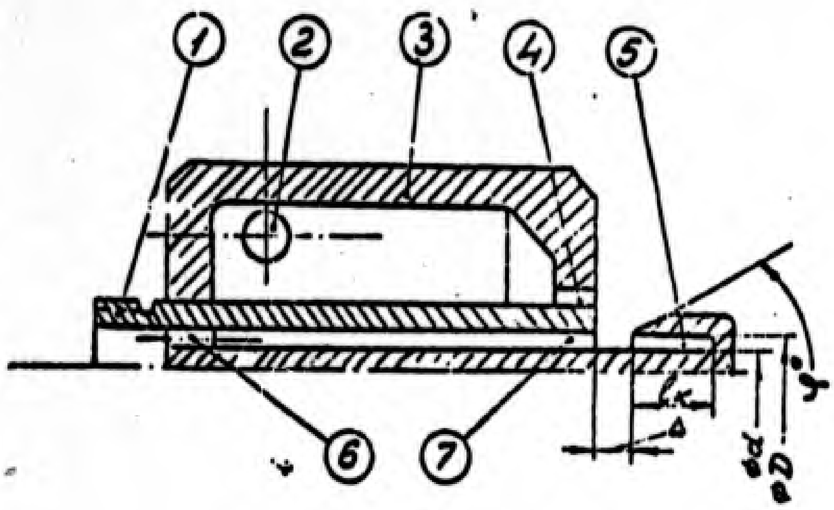

Fig. 1. Diagram of injector with generator: 1 — generator casing; 2 — liquid inlet into chamber; 3 — injector casing; 4 — radial clearance for liquid outlet; 5 — generator chamber with rod; 6 — air inlet; 7 — air outlet through annular nozzle.

The generator comprises an annular chamber, which on the side of the air inlet has a sharp edge with an angle of $\varphi \leq 30^{\circ}$. The chamber is braced to the injector casing 3 as shown in the diagram.

On the basis of operation of the gas generator, there is taken the process of outflow of the supersonic gas jet ($M \geq 1$) from the nozzle with excess pressure in the jet. In connection with the excess of speed of gas over the speed of sound propagation in this gas, the flow acquires a periodic structure. On sections where the pressure increases, the flow is unstable (regions of instability: first, second, etc.).

The resonator-chamber of the gas generator 5, installed in the region of instability, gives sound and ultrasonic vibrations. Research related to determination of the length of the first region of instability was conducted for the first time by Emden [1]; he obtained empirical formula

$$\Delta = kD\sqrt{P_p - 1.9},$$
[p = r = receiver] (1)

where Δ – length of the first region of instability (in the work it is called clearance Δ);

D – nozzle diameter;

P_r – air pressure in the receiver;

$k = 0.77\text{-}1.02$.

Prandtl attempted to substantiate his experimental data theoretically. However, the coefficient obtained by Prandtl $k = 1.2$ is very great, and his assumption on the average state of the jet – state of the jet on the nozzle outlet, is erroneous.

Pack [1] offered to take parameters of the jet at the nozzle exit in the initial period of expansion at maximum distance from the axis of the nozzle. He obtained the formula for the length of the first part

$$\Delta = 1{,}22D\sqrt{M^2 - 1}, \quad (2)$$

where M = Mach number.

To formula (1) for pressure $P_r = 4.5$ kg/cm^2 = const. Pack recommends $k = 1.12$; for the second and subsequent periods of a jet with pressure $P_r = 3.5\text{-}7.5$ kg/cm^2, $k = 1.06$.

On the basis of experimental data for M = 1, Hartman [2] reduces the emperical formula for determining distance l from the nozzle exit to the resonator

$$l = D[1 + 0{,}04(P_p - 0{,}93)^2]. \quad (3)$$

Hartman does not give the length of the first region of instability.

For the case of small differences of pressures in the jet and environment, empirical formulas of the length of the first region of instability are given when $P_{ext} = P_2 = 1$ atm (abs.) [3, 4].

$$\frac{\Delta}{D} \approx 0{,}89 \sqrt{P_p - 1{,}9}, \tag{4}$$

$$\frac{\Delta}{D} \approx 0{,}9 \sqrt{P_p - 1{,}9}. \tag{5}$$

In 1959 Love and others [5] published a work, in which they offered a semiempirical formula for determination of length Δ.

In [7], conducted on the basis of the theory of turbulent streams [8] under the direction of G. N. Abramovich, an empirical formula for determination of the length of the first region of instability (they sometimes call it the first "roll") of axisymmetric flow is given

$$\text{for } n \leqslant 2 \qquad \bar{\Delta} = A, \tag{6}$$

$$\text{for } n > 2 \qquad \bar{\Delta} = A\left(\frac{n}{2}\right)^{t}, \tag{7}$$

where $n = \dfrac{P_o}{P_{ext}}$ (here P_o — air pressure at the nozzle outlet; P_{ext} — pressure of external air);

$$\bar{\Delta} = \frac{\Delta}{R_{вых}},$$

[ВЫХ = o = outlet]

R_o — radius of nozzle;

$$A = 3{,}1\, M_{вых}^{1/4} \left[\sqrt{nM_{вых}^2 - 1} - \sqrt{M_{вых}^2 - 1}\right] + 2\sqrt{M_{вых}^2 - 1};$$

$$t = \frac{0{,}523}{\sqrt{M_{вых}}} \quad \text{for } M_{вых} < 1{,}5;$$

$$t = 0{,}451 - 0{,}016\, M_{вых} \quad \text{for } M_{вых} \geqslant 1{,}5.$$

This formula will better agree with experimental data obtained in Moscow Aviation Institute (MAI) and NASA than the formula offered by Love [5].

As it is known, theoretical works on the determination of the length of the first region of instability is not published. The case [3] of application of the theory of small perturbations for small angles θ, is considered, so, for plane flow

$$\frac{\Delta}{D}=2\sqrt{M^2-1}-\frac{2}{\operatorname{tg}\mu}, \tag{8}$$

for axisymmetric flow

$$\frac{\Delta}{D}\approx 1{,}306\sqrt{M^2-1}-\frac{1{,}306}{\operatorname{tg}\mu}. \tag{9}$$

Works on the determination of this length for the outflow of a supersonic gas jet from the annular nozzle with excess pressure in the jet are not published.

The author calculated the length of the first region at ratio (D - d)/D, equal to 10-20%.

Change of pressure and speed are presented in Fig. 2a and b. This flow, directed into the generator chamber, causes the appearance of a shock wave, which starts to vibrate with a definite frequency (Fig. 3). Under the influence of excess pressure, appearing after the shock, the latter will start to shift into the area of high speeds. Excess pressure (dotted line A, Fig. 2c) appears due to the outflow of gas from the resonator into the wind. Then the shock moves to the oposite side due to its drop of pressure (dotted line B, Fig. 2c), since in this case air pressure in the resonator will drop.

In case of the outflow of gas through the annular nozzle,we will assume the gas pressure in the stream P_a to be larger than the

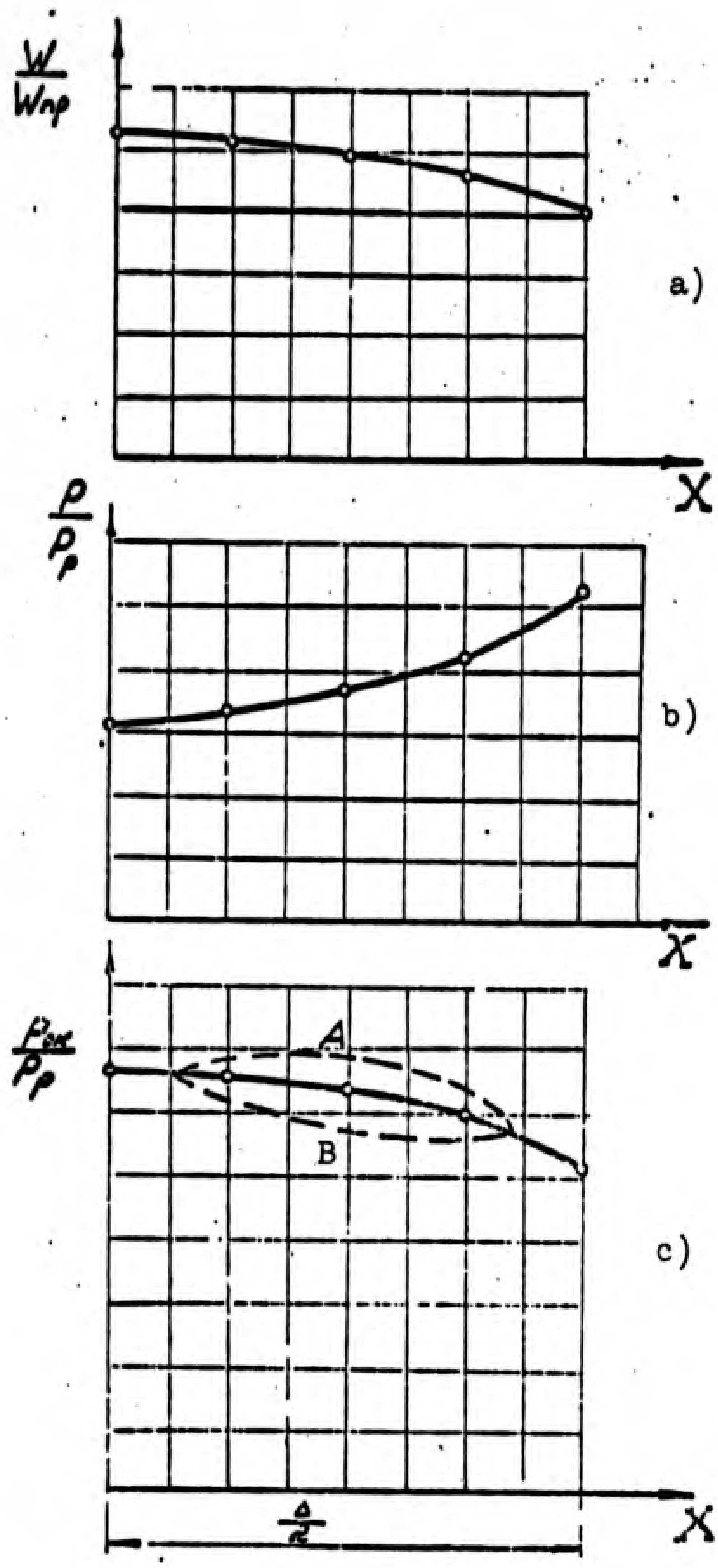

Fig. 2. Mean parameters of supersonic flow: a) change of relative speed along the axis on a section of the nozzle exit; b) change of relative pressure; c) change of relative pressure after the shock.
[пр = m = maximum, ск = sh = shock].

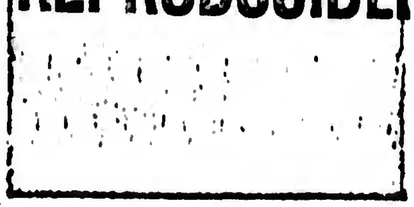

Fig. 3. Oscillogram of vibrations of air pressure in generator chamber.

ambient pressure P_{ext}. Foreign gas is motionless; mixing with it is not considered, since the examined portion and time of interaction are small. Viscosity is not taken into account. Then plane-parallel flow along the solid wall acquires a structure as shown on the diagram of Fig. 4. Since along line AC the pressure should be equal to P_{ext}, then at point A are formed rarefaction waves, reflecting from the solid wall at points a, o. Rarefaction waves are reflected from the boundary as compression waves. Angle θ is determined from the condition of expansion of flow $M \geq 1$ for sharp edge from P_a to P_{ext}.

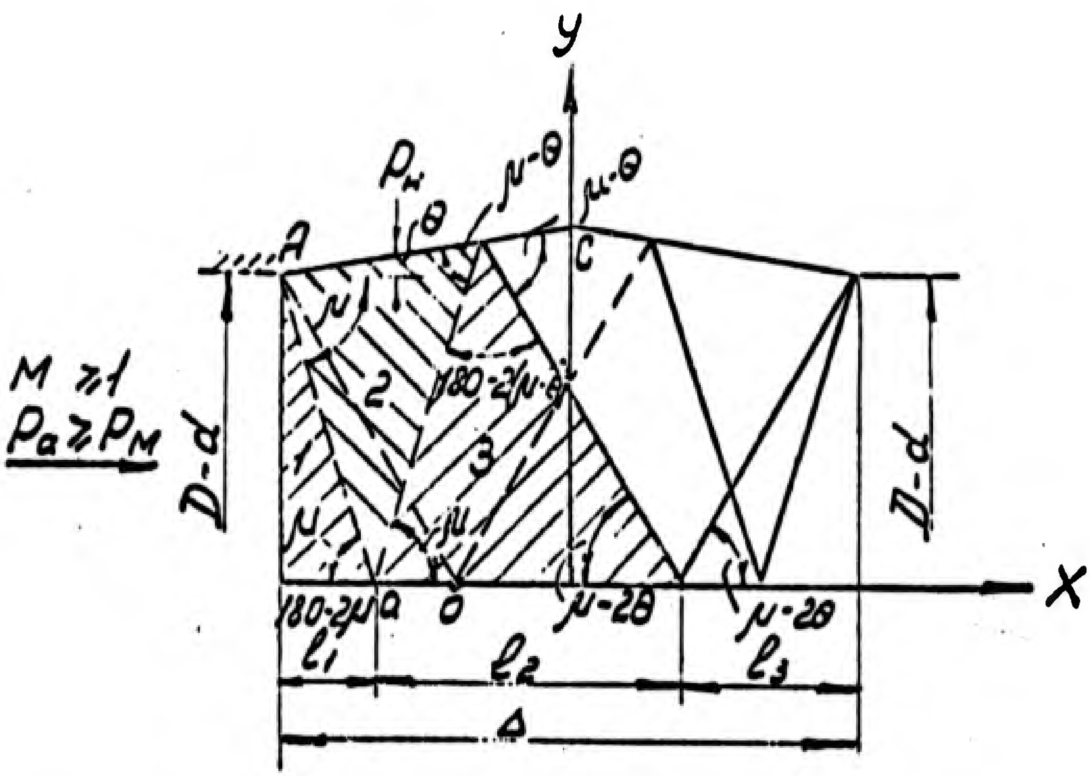

Fig. 4. Diagram of plane-parallel flow.
[н = ext = external]

Clearance Δ of the gas generator for a plane-parallel flow is determined through available values of μ, θ by the following formulas:

$$l_1 = \frac{D-d}{2}\operatorname{ctg}\mu, \qquad (10)$$

$$l_3 = \frac{D-d}{2} \operatorname{ctg}(\mu - 2\theta). \quad (11)$$

Determining triangles 1, 2, and 3 consecutively, we obtain

$$\overline{l_3} = \frac{D-d}{2} \frac{\sin(\mu+\theta)\sin^2(\mu-\theta)}{\sin(\mu-\theta)\sin\mu\sin(\mu-2\theta)}. \quad (12)$$

Lowering the simple trigonometric transformations, finally for $\Delta = l_1 + l_2 + l_3$ we obtain

$$\frac{\Delta}{D-d} = \frac{2}{\operatorname{tg}(\mu-\theta) - \operatorname{tg}\theta}. \quad (13)$$

The axisymmetric flow in the meridian section is possible to consider as plane-parallel, if the outflow of gas occurs through the annular nozzle with a small ratio of clearance to radius.

It is known [6] that for the potential flow of gas, the equation for plane-parallel flow will be recorded

$$H\frac{\partial U}{\partial x} + L\frac{\partial V}{\partial y} + 2K\frac{\partial V}{\partial x} = 0, \quad (14)$$

axisymmetric flow

$$H\frac{\partial U}{\partial x} + L\frac{\partial V}{\partial y} + 2K\frac{\partial V}{\partial x} + N = 0, \quad (15)$$

where $H = 1 - \frac{U^2}{a^2}$; $L = 1 - \frac{V^2}{a^2}$; $K = -\frac{UV}{a^2}$, $N = \frac{V}{y}$;

U and V — components of the speed of W along axes X, Y; a — speed of sound.

Characteristics of equation (14) have the form

$$\frac{dy}{dx} = \operatorname{tg}(\theta \pm \mu); \quad \frac{dW_{np}}{W_{np}} \pm d\theta \operatorname{tg}\mu = 0, \quad (16)$$

and equation (15)

$$\frac{dy}{dx} = tg(\theta \pm \mu); \qquad \frac{dW}{W_{m}} = \pm d\theta\, tg\mu - \frac{dx}{y}\,\frac{\sin\mu \sin\theta\, tg\mu}{\cos(\theta \pm \mu)}, \tag{17}$$

where W_m — ratio of rate of flow to maximum velocity during the expansion of gas $P_{ext} = 0$;

μ — Mach angle.

A solution of equation (17) in analytic form is not found.

In plane-parallel flow during expansion at the sharp edge the rate along each characteristic remains constant with respect to magnitude and direction.

On the sharp edge of the nozzle in plane Y, parameters of flow are determined from equation (16). Characteristics (17) can be replaced by their tangents. We determine parameters of flow along these tangents by equation (16).

However, when using equation (16) instead of (17) (which is of interest for engineering calculations), it is necessary to estimate the greatest possible error appearing with this. For this we use equation (17) in finite differences for the right characteristics related to flow

$$\Delta x = \frac{|\Delta y|}{tg(\mu + \theta)},$$

then the last term of equation (17) will be expressed

$$m = \frac{\Delta y}{y}\,\frac{\sin\mu \sin\theta\, tg\mu}{tg(\mu + \theta)\cos(\theta + \mu)}. \tag{18}$$

Converting equation (18), we will obtain

$$m = \frac{|\Delta y|}{y}\, tg\mu \frac{tg\theta}{1 + \cfrac{tg\theta}{1 + \cfrac{tg\theta}{tg\mu}}},$$

we will designate

$$\frac{\operatorname{tg}\theta}{1+\dfrac{\operatorname{tg}\theta}{1+\dfrac{\operatorname{tg}\theta}{\operatorname{tg}\mu}}} = A.$$

As can be seen during the change $\theta < \mu < 90^{\circ}$; $A \leq \operatorname{tg}\theta = K$. Let us replace $A \operatorname{tg}\mu = Z$, then

$$m = Z\frac{|\Delta y|}{y}. \qquad (19)$$

The relative error in the determination of rate

$$|\delta| = \left|\frac{m}{1+m}\right| 100\%.$$

Assigning: $\delta \leq 5\%$, we obtain $m \approx 0.05$; $\frac{\Delta y}{y} = 0.1$, we receive $Z = 0.5$; $\theta_{max} = 20^{\circ}$ we have $A \leq \operatorname{tg} 20^{\circ} = 0.3697$. Then

$$\operatorname{tg}\mu = \frac{Z}{A} = \frac{0,5}{0,3697} = 1,35$$

$$\mu \approx 50^{\circ}30'; \qquad M \approx 1,25.$$

Thus, with sufficient accuracy for practice, axisymmetric flow-in the meridian section can be considered as plane-parallel when air pressure is $P_{air} \geq 2.5$ atm (abs.) and the pressure of external air $P_{ext} = 1$ atm.

We find the functional dependence of Δ through Φ. For this we will designate

$$\Phi = \operatorname{tg}(\mu - \theta) - \operatorname{tg}\theta. \qquad (20)$$

Having the function, expressed by equation (20), we construct dependence:

$$P_B = f(\mu), \qquad \Phi = f(\mu) \text{ and } \Phi = f(\Delta),$$

[B = air]

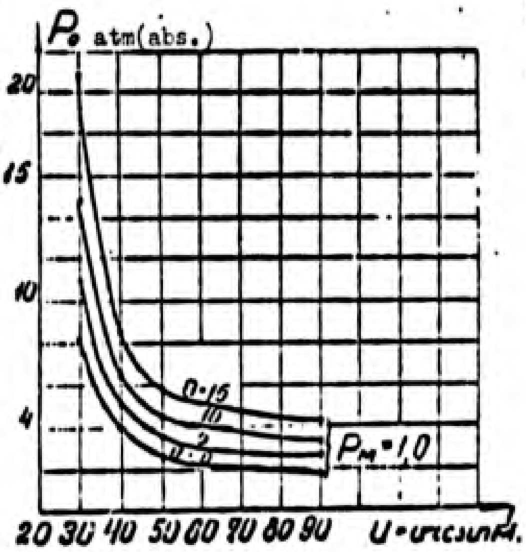

Fig. 5. Dependence of M and θ at the nozzle exit on the pressure in the receiver when P_{ext} = 1 atm.

which are presented in Figs. 5 and 6.

Using known [9] relations $l_c = D$ and $\lambda = 4(l_c + 0.3D)$, we obtain the geometric dimensions of the chamber of the generator (where λ – frequency of oscillations; l_c – length of chamber).

In Fig. 6 for comparison, we plotted dependences given by equations (3), (4), (5), (8), (9). On the basis of equation (13) and dependences given in Figs. 5 and 6, the following diagram of calculation of clearance Δ is offered:

1) by the specified expenditure and total pressure of gas, having selected M ≥ 1, we define D and P_a at the nozzle exit;

2) by M ≥ 1 and $P_a > P_{ext}$ we find θ;

3) we determine the ratio of $\frac{\Delta}{D - d}$ and magnitude Δ.

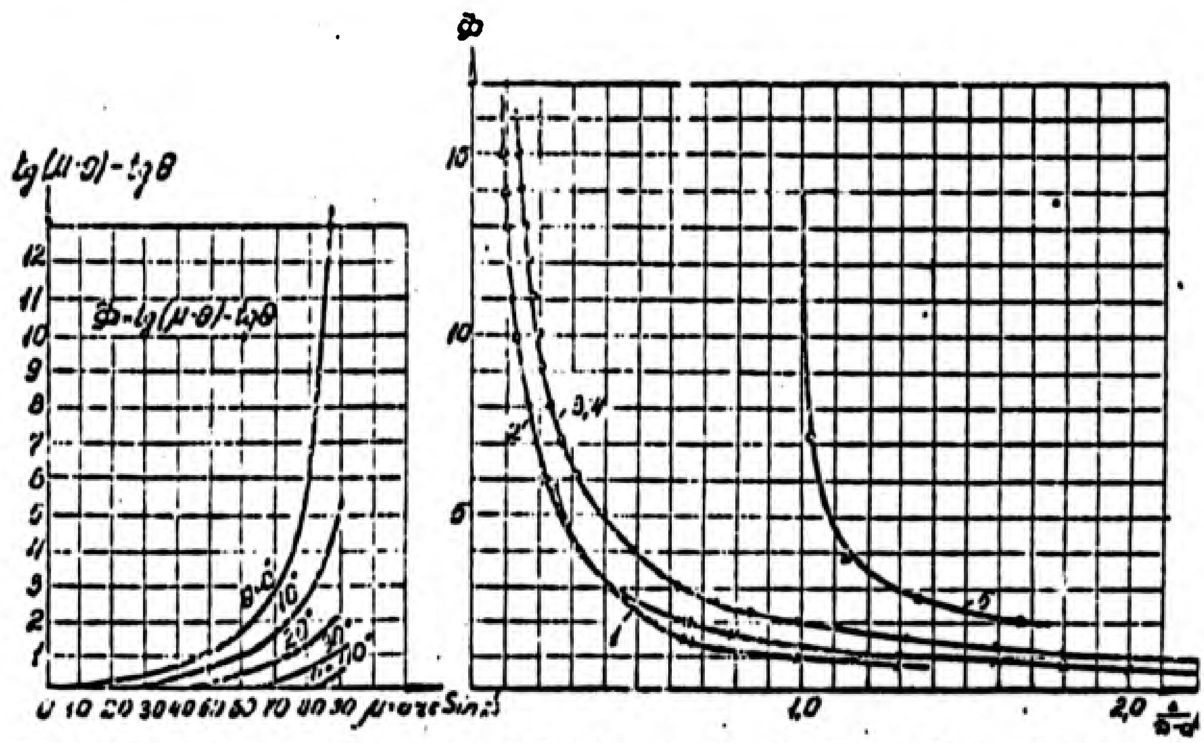

Fig. 6. Determination of clearance Δ from the charge of M, θ when P_{ext} = 1 atm:
$1 - \frac{\Delta}{D} \approx 0{,}9\sqrt{P_p - 1{,}0}, \theta \approx 0$; $2 - \frac{\Delta}{D} \approx 1{,}306\sqrt{M^2 - 1}, \theta \approx 0$; $3 - \frac{\Delta}{D} = 2\sqrt{M^2 - 1}$, $\theta \approx 0$; $4 - \frac{\Delta}{D - d} = \frac{2}{\lg(\mu - \theta) - \lg\theta}, \theta \leq 20°$; $5 - \frac{l}{D} = 1 + 0{,}043(P_p - 0{,}93)^2, M = 1$

Example of Calculation of the Clearance of a Generator with an Annular Nozzle

1. On the graph presented in Fig. 5, we draw the vertical for $\mu = 60$, which corresponds to $M = 1.144$.

2. On the same graph we draw the horizontal, corresponding to a gas pressure of 4 atm (abs.). The point of intersection determines $\theta = 10^\circ$.

3. On the graph of Fig. 6 we draw the vertical, corresponding to $\mu = 60$ until intersection with $\theta = 10^\circ$.

4. By obtained value $\Phi = 1$, we find $\frac{\Delta}{D - d} = 1.38$.

5. By given $Q_{air} = 32.5$ kg/hr and $M = 1.144$, we determine D - d at the nozzle exit, then $\Delta = 1.38\ (D - d)$.

Since D = 12 mm, and d = 11.5 mm, then

$$\Delta = 1{,}38(12{,}0-11{,}5) = 0{,}69 \text{ мм}.$$

By this method, the injector generator was calculated, prepared and tested at differential water pressures up to 6 atm (gage). We received the mean diameter of drops within limits of 130-80 μ. The dependence of $d_{mea} = f(P_{air})$ is presented in Fig. 7.

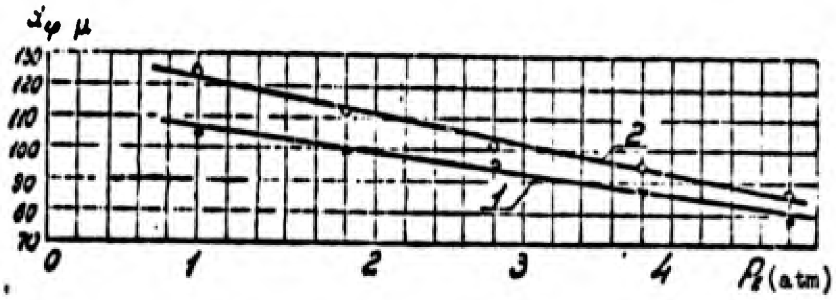

Fig. 7. Dependence of mean diameter of drops on the pressure of liquid on entrance into the injector: 1 — casing No. 1; 2 — casing No. 3. [cp = mea = mean]

Conducted analysis shows that the annular flow with small radial clearance (10-20% with respect to radius) approaches the plane flow.

For the plane flow we obtained equation (13)

$$\frac{\Delta}{D-d} = \frac{2}{\operatorname{tg}(\mu-\theta)-\operatorname{tg}\theta},$$

which coincides with the equation of Pai Shih-i (curve 3, Fig. 6).

The presented method of calculating the clearance Δ of an injector generator makes it possible to obtain qualitative atomization of liquid and to achieve a reduction of liquid pressure on entrance into the injector.

Theoretical and experimental data concerning this question were partially published [10, 11].

The clearance, determined by Hartman's empirical formula (3), reaches great magnitudes (curve 5, Fig. 6), which eliminates the source of sound from the flowing liquid and worsens the quality of liquid atomization, since the dissipation of sound energy is observed Hartman's formula is correct for M = 1.

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