PROCESSES IN THE CHAMBER OF LIQUID ROCKET ENGINES

GENERAL INFORMATIONS

Complexity of creation of the chamber with perfect technical datas (high specific impulse, small weight and overall dimensions) is connected to extremely intense working process in the chamber.

To receive higher specific impulses of LPRE high-grade fuels are used. Combustion happens at high pressure in the combustion chamber to consequent large expansion ratio of products of combustion in the nozzle.

The modern reference fuels on basis of HNO_3, and N_2O_4 and liquid oxygen have heating value, in some times exceeding heating value of fuel in any other thermal machine. Now implant more efficient of fuel (hydrogen + oxygen or a fluorine, metallic fuel).

At use of these propellants, depending on principal design of LPRE, combustion-chamber pressure reaches tens megapascal, exhaust velocity of gases — 2500-4500 m\s, combustion temperature is 3000-4000K and higher. Therefore it is difficult to protect walls of the chamber from thermal, corrosion and erosive effect of a gas stream by methods which do not entail a decreasing of specific impulse and increase of weight of LPRE. Not smaller complexity is represented with a problem of combustion of fuel in a restricted volume.

Fuel in the combustion chamber is during several thousand fractions of a second and that it to burn with sufficient completeness of combustion, special preparation of fuel specific for combustion chamber is necessary.

Propellant components move through centrifugal or spray nozzles and outflow from them as a thin film of the cone-shaped form or as jets which disintegrate on separate drops. At close arrangement of it spray patterns or jets of fuel even before disintegration on drops interreact each with other, and at far arrangement of injectors a spray pattern or a jet disintegrate up to a meeting with each other and further interreact as drops.

For combustion of propellant in a minimum volume of the combustion chamber it is necessary, that mixing elements of the head uniformly arranged fuel in cross section of the combustion chamber both on flow rate intensity, and on a structure of propellant, close to mean components ratio of propellant for the combustion chamber as a whole.

PHYSICAL FUNDAMENTALSES OF WORKING PROCESS IN THE COMBUSTION CHAMBER

TOTAL CHARACTERISTIC OF PROCESS

Physical and chemical transformations of the fuel, component working process in the combustion chamber, should be organized so that to ensure maximum completeness of combustion of fuel and a steady leakage of processes in the chamber, necessary for reliable and a safe work of the engine.

Transformation of fuel into combustion products happens by degrees. As a result of atomization and jet dispersion of propellant components going from injectors form drops of the different sizes. At the expense of the heat going from a burning zone, drops of components are heated and evaporated; gaseous fuel and oxidizing agent mix up, during mixing exothermal gas-phase reactions of combustion take place.

In the chambers working under the scheme gas — liquid or gas — gas, the processes connected to heating and a gasification of one or both components, are eliminated. Sometimes propellant components can in part or completely mixed in a mixing element before injection in the combustion chamber. If components auto ignite reactions of combustion can begin at mixing of components in a liquid phase or there can be heterogeneous reactions.

Formation of an atomization plume is a random process. Measurements show, that in the same point near to the mixing head drops of the different sizes are formed, and even equal drops have different velocities. Therefore such parameters of atomization as the diameter of drops and their velocity in any point of the chamber are aleatory variables and the description of characteristics of atomization needs statistical consideration with used of distribution functions.

Empirical cumulative distribution functions are applied, their parameters find on experimental researches of spectra of an atomization. The median diameter of drops varies within wide range of limits and makes 25...500 microns.

MIXING OF COMPONENTS

The random distribution of components ratio κ_m and flow rate intensity on the area of the mixing head is of great importance for reaching high performance of combustion — full heat release in a minimum volume. Experiments display, that to non-uniformity of components ratio on cross section which scale surpasses a step between injectors, level off at motion on the combustion chamber a little and result in poor combustion of fuel.

Liquid-phase mixing is possible for heads of the chambers working under the scheme a liquid — a liquid. Formation of a mixture happens at collisions of jets, sheets or separate drops of components at interception of plumes of atomization; organization of mixing of jets on surfaces — a special barrier (plates) is possible. Advantage of liquid-phase mixing is the small volumes necessary for its implementation.

For heads of the chambers working under the scheme gas — liquid, mixing of components happens in some volume of the chamber in transport process and gasification of drops in gas medium (products of gas generation, an incomplete combustion or vapor of a component). The same mechanism in part or completely acts and in heads of the scheme a liquid — a liquid at interpenetration of plumes of atomization, at their natural expansion.

Final mixing of propellant components happens in a gas phase and is provided in main with turbulent diffusion. In case of the thin atomization and fast gasification of components, and also at interaction liquid and gas jets on exit bicomponent coaxial gas- liquid injectors gas-phase mixing can be determining process for reaching high completeness of combustion.

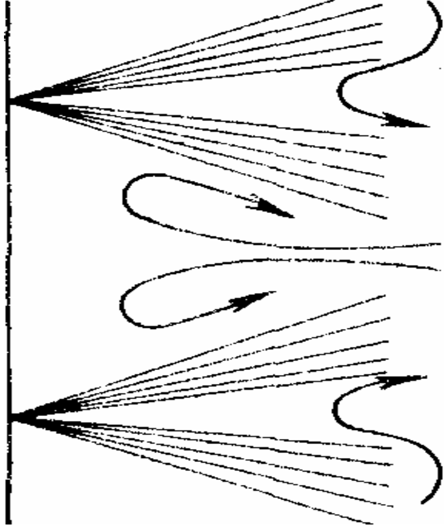
Mixing in a gas phase, and for autoigniting propellents and in a liquid phase, is accompanied by chemical reactions which work upon process of mixing, for example, disjoint jets of components and slow down mixing, or, on the contrary, create turbulence a flow and promote mixing.

SINGULARITIES OF MASS TRANSFER BETWEEN PHASES

Mass transfer between liquid and gas phases take place together with heat exchange and is accompanied by chemical reactions in gas, and sometimes and in liquid phases. Quantity of heat, required for a warm-up and evaporation of drops, can be the considerable. On a mode of an engine start-up the heat supply for a heating and evaporation of a part of components implements from the special ignition device (it is not required for autoigniting main or firing components), and on steadied — from a zone of developed combustion.

In the latter case only the minor part of necessary heat is made from combustion zone by radiation and heat conduction, the main weight of heat goes at the expense of convective diffusion. The main role in this phenomenon is played with so-called "reversed currents". They result from inducing effect at exchange of momentum between injected components and products of combustion. The component entrains behind itself passing gas currents, is simultaneous with which there are also revertive (recirculation) currents (see figure). The recirculation gas flow can comprise of a unreacted gas phase of components and products of combustion.

Effect of reversed currents on working process can be different. It depends on a scale — a step between injectors, character of atomization (jets, centrifugal atomization, etc.), a structure and temperature of products of combustion. Decreasing of a step between injectors results to that the majority of cross-section is filled by plumes of atomization, the zone of reversed currents is



narrowed down also requirements of a convective heat supply from combustion zone become worse.

"Reversed currents" at the head of the chamber

Excessive increase of a step between injectors besides aggravation of e(mixing) can make more intense thermal operating conditions of the head which in this case "is open" for hot reversed currents. The pressure increasing in the combustion chamber promotes intensification of convective diffusion of heat.

Calculations of motion of evaporating single drops in a medium of products of combustion display, that length of a segment of the combustion chamber, necessary for full evaporation of drops of the fixed size, is reduced at decreasing of initial velocity of drops, at increasing of pressure in the combustion chamber and a velocity of gas. It can be reached, for example, by decreasing of the relative area of the combustion chamber. The length of a segment of full evaporation is reduced also at increase of temperature of drops in outcome, for example, a heating of a component before the chamber. At the same time rather large change of temperature of gas in the combustion chamber does not render apparent effect on rate of evaporation.

Combustion-chamber pressure of the modern LPRE frequently exceeds critical pressure of an injected liquid component. After heating of a drop to critical temperature it at once passes in a gaseous state (it is not required renderings of heat of phase change), and "fuzzying" of a drop is determined by diffusion processes. If to count fair the supposition about instantaneous allocation of weight, and a drop

— its point source distribution of density of substance of a drop on radius R in an instant τ can be found by formula

$$c(R,\tau) = \frac{r_3^3 \rho_{ж}}{3\sqrt{4\pi}(RD)^{3/2}} \exp(-R^2 / 4D\tau)$$

where D — a factor of eddy diffusion.

COMBUSTION

Characteristic difference of LPRE's combustion chambers is absence of front stabilizing devices due to which there are requirements for formation of steady flame front. The mixing, inflaming and fixed combustion in LPRE provide without such devices for the score concerning low speeds of motion of a medium in a zone of preparation and combustion and mainly at the expense of the mechanism of carry of heat with reversed currents. In a zone of preparation of fuel it is possible to term circulation of combustion gases natural stabilization of a flame.

The mix in the combustion chamber (except for the scheme gas — gas) in a considerable proportion of processes of transformation of fuel is two-phase. Interaction of phases among themselves, heat rejection from products of combustion, strongly developed flow turbulence and diffusive flows accelerate preparatory processes and naturally combustion. The general picture of all complexes of phenomena is very complex and largely depends by nature of fuel, a design of the combustion chamber and a system of a mixing.

For hypergolic propellants exothermal reactions in a fluid phase, proceeding already at a contact (mixing) of jets or drops of components, are characteristic. Heat effect of these reactions promotes evaporation of drops, including what did not react in a fluid phase as did not interfere with drops of other component. At mixing of vapours of fluid and an oxidizer chemical reactions in a gas phase, resulting in to formation of termination products of combustion are proceed. Combustion of gaseous fuel and an oxidizer is homogeneous.

Selecting different kinds of combustion, it is necessary to mark also a heterogeneous combustion which happens on a phase boundary. One of reactants is in a liquid phase; another is delivered to a surface by diffusion from a gas phase. However in most cases from a surface of a drop there is a flow of vapour and combustion happens during mixing of it vapour to the second component present in a gas phase. It is possible to term such combustion diffusive quasi-heterogeneous.

If liquid propellant components move in the combustion chamber at supercritical pressure, after heating of drops to critical temperature process of combustion differs quality and quantitatively from combustion of drops at subcritical pressure. At supercritical parameters surface layers of a drop represent "bunch" of molecules and a velocity of processes of combustion is determined by its diffusive fuzzying and convective diffusion.

On the basis of outcomes of experimental researches process of stationary combustion can be characterized as follows. Combustion is in basic homogeneous, with an essential chemical non-uniformity and a turbulence which character is completely determined by a system of a mixing.

Some part of fuel in the form of the largest drops burns out on regularity heterogeneous or quasi- heterogeneous combustion. The combustion zone of rather large expansion with diffusion outlines is observed. Reasons of it is the superposition against each other preparatory processes and processes naturally combustion, and also a widescale turbulence and local breaks of flame front.

However on some distance from the head (about several millimeters) it is possible to mark out conditional flame front of small width. In its limits the main body of heat is produced. Process of combustion is characterized by a non-uniformity of fields of a structure, temperatures and velocities, defined arrangement of injectors. The decreasing of temperature of gas near to walls of the combustion chamber is possible.

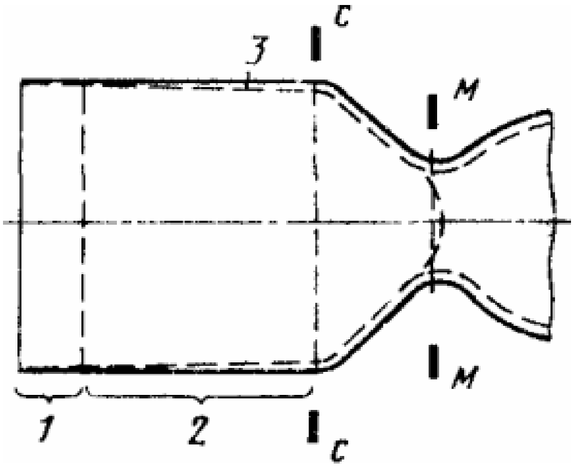
PRINCIPLES OF CONSTRUCTION OF MATHEMATICAL MODEL OF THE ATOMIZED FUEL COMBUSTION

Mathematical models of working process in the combustion chamber develop for calculation of parameters of a mix in its volume, including on an input in the nozzle. Values of these parameters allow to estimate effect of working process in the combustion chamber on flow parameters in the nozzle. On the basis of mathematical model it is possible to estimate effect of separate factors (the sizes of drops, models of interaction of drops among themselves and with a gas phase, etc.) on process of transformation of propellant.

Construction of enough precise theoretical models of different physicochemical and hydrodynamic phenomena in the combustion chamber, apparently, is impossible for the lack of data on many elementary mechanism of interaction.

Depending on a aggregate state of components on an input in the mixing head (a liquid — a liquid, gas — a liquid, gas — gas) at construction of mathematical model of working process it is possible to evolve different limiting physical factors. For example, in case of a system a liquid — a liquid process can be limited by rate of evaporation of liquid components. For a system gas — the liquid the determining factor can be both rate of evaporation, and a velocity of stirring with a liquid of jets of injected gas, and then — a velocity of stirring of gaseous jets with different chemical composition.

At construction of mathematical model on the basis of known quality relations of change of temperature longwise combustion chambers, its volume conditionally subdivide into different zones (see figure).



The scheme of working process in the combustion chamber

1 - a zone of a mixing; 2 — an evaporation and combustion zone;
3 - area of a boundary layer

The zone of a mixing (input, atomization and premixing of propellant components), adjoining to the mixing head of the chamber, practically does not give in to mathematical simulation.

Therefore parameters of a two-phase medium on escaping of this zone set on the basis of experimental data for a condensed phase (the distribution function of drops on the sizes) and some assumptions concerning a structure and other properties of a gas phase.

So, for the scheme a liquid — a liquid it is believed, that a gas phase in a zone of a mixing are vapours of injected components and the light-end products of combustion fallen in a zone with reversed currents.

In case of the scheme gas — a liquid it is believed, that a gas phase are products of gas generation at known components ratio and vapours of an injected liquid component.

Parameters in an evaporation and combustion zones calculate on the basis of the theory of non-equilibrium two-phase flows. In equations and the formulas obtained on the basis of this theory, it is necessary to take into account effect of evaporation on particle sizes, heat transfer and friction between gas and particles (drops), change of a structure of a gas phase longways combustion chambers because of evaporation and non-equilibrium chemical reactions in a gas phase.

Parameters of a two-phase mixture on escaping of a zone of a mixing consider known. The outcome of calculation is a distribution of parameters longways chambers. For calculation non-equilibrium two-phase gas-liquid flows different mathematical models can be utilized.

On the basis of mathematical model approximated theoretical researches only some special problems of working process can be made. For example, the curve of a born-out can be calculated, phase of delay τ_3 for research of dynamic characteristics of the combustion chamber is estimated.

In formed practice of designing of the combustion chamber satisfactory outcomes can be obtained at use of enough simple empirical formulas.

THE THEORY AND CALCULATION OF MONOPROPELLANT INJECTORS WITHOUT TAKING INTO ACCOUNT VISCOSITY OF PROPELLANT COMPONENTS

For combustion of propellant in minimum volumes of the combustion chamber its head with mixing elements should ensure more uniformly distribution of propellant in cross section of the combustion chamber. The size of drops of propellant fed to the combustion chamber should be as more as possible even and small enough that it is simultaneous and process of their evaporation was faster completed. A positional relationship of injectors of fuel and an oxidizer and their hydraulic parameters should promote a random distribution of propellant, provide the heat input from the combustion chamber to the atomized propellant for its evaporation and to create requirements for stirring of propellant components. Thus large value selection of type of injectors, their characteristics and a positional relationship of injectors of fuel and an oxidizing agent have.

Let's consider a fundamentals of the theory and calculation of mixing elements of the head — jet and centrifugal injectors.

In a LPRE two types of injectors are widely used: centrifugal (fig. 1, a) and jet (fig. 1, б).

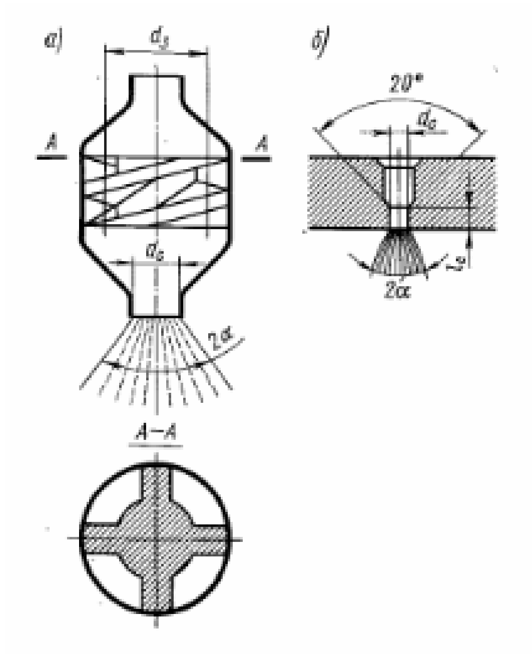


Fig. 1. Schemes of a centrifugal injector with a screw (a) and a spray injector (б)

The spray injector submits propellant components as a compact jet which, at characteristic for a LPRE small pressure differentials, disintegrates on sizable drops. Thus the angle of atomization of spray injector is insignificant: $2\alpha = 5 \div 20^{\circ}$, and range large enough. Therefore with the help of spray injector s it is difficult to receive the good mixing ensuring complete combustion of fuel in a minimum volume of the combustion chamber. To improve quality of a mixing it is possible at the expense of collisions of jets of the propellant components, given several spray injectors, or impact of a jet about a special surface and its consequent destruction (fig. 2).

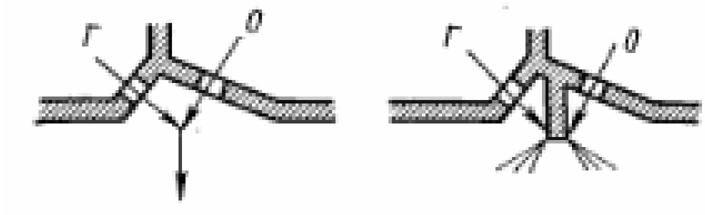


Fig. 2. Ways of stress rupture of a jet

Productivity of a spray injector

$$\dot{m}_{ф} = \mu_{ф} F_{cф} \sqrt{2\rho \Delta p_{ф}} \ . \qquad (1)$$

where $\mu_{ф}$ — a flow rate coefficient of an;

$F_{cф}$ — The area of a injector jet;

ρ — Liquid density;

$\Delta p_{ф} = p_{0ф} - p_{K}$ - a pressure differential on an injector, equal difference of pressures on an input in an injector and in the combustion chamber.

The flow rate coefficient of an injector, equal to the ratio of the true flow rate to theoretical it of a liquid, always is less than unit because of jet contraction in the nozzle and decreasing of true exhaust velocity because of hydraulic resistances. A flow rate coefficient for a spray injector determine experimentally.

The strong effect on value of a flow coefficient renders the ratio of length of a cylindrical part of the nozzle to its diameter $\frac{l_c}{d_c}$. So, at $\frac{l_c}{d_c}$ = 0,5÷1 a flow coefficient $\mu_{ф}$= 0,6÷0.65, and at 2 < $\frac{l_c}{d_c}$ <5 coefficient increase up to $\mu_{ф}$ = 0.75-0,85.

Hence, a factor $\mu_{ф}$ at spray injectors is enough large and as it will be shown further, is more, than at centrifugal injectors. An entrance angle 2θ in a injector jet, a kind of a liquid, its temperature, pressure of a medium where fuel is injected effect on a flow rate coefficient $\mu_{ф}$,. For example, increasing of a medium pressure can prevent a flow separation in a injector jet and by that to increase value of $\mu_{ф}$, as contrasted to the value obtained at hydraulic testings in atmospheric conditions.

Spray injectors have been extended in the LPREs working on autoigniting propellant components where it is not required the thin atomization of fuel, and also in a LPRE with small cross sectional dimensions of the combustion chamber.

In the latter case it is difficult to place necessary quantity of swirl injectors, which could ensure of supply of large weights of propellant at small pressure differentials on injectors on the head of the chamber. The spray injectors which have great value of $\mu_{ф}$, provide supply of large weights of propellant at permissible differences $\Delta p_{ф}$ through the head of chambers of small cross sectional dimensions.

The principle of operation of centrifugal injectors differs from a principle of operation of spray injectors.

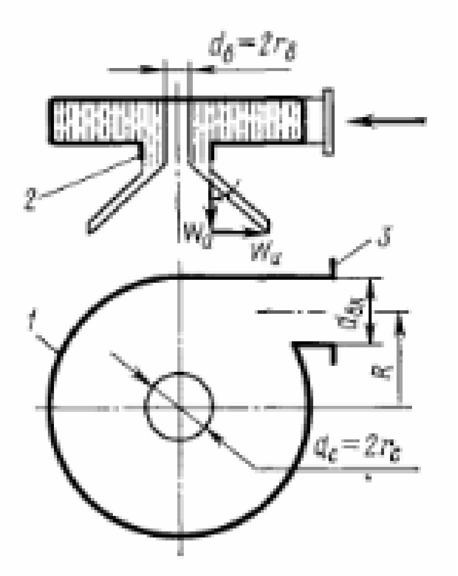


Fig. 3. The computational scheme of a centrifugal injector

In a centrifugal injector 1 (fig. 3) the liquid moves through a tangential input channel 3. Therefore the moment of momentum of a flush on an input in an injector concerning an axis of the nozzle is not equal to null and a liquid, being twirled, flows through an injector. On exit of the nozzle 2 jet will be transformed to a film of a taper which under an operation of centrifugal forces disintegrates on drops further. In the space drops fly apart on straight paths, tangent to their former trajectories (cylindrical surfaces, coaxial with an injector exit nozzle).

The tangent of an angle of straight paths of drops with an axis of an injector will be equal:

$$tg\alpha = \frac{W_u}{W_a}, \qquad (2)$$

where W_u, W_a are circumferential and axial component velocities outlet from the nozzle.

The centrifugal injector, depending on its geometry parameters can change over a wide range at the given pressure differential its key parameters (an angle of atomization of liquid and a flow rate coefficient of an injector). The geometry of an injector also influences value of the drops which are generated as a result of destruction of conical film. It allows the designer to influence simple methods organization of process of a mixing.

Let's consider regularities of ideal flow in a centrifugal injector which computational scheme is shown on fig. 3. In view of absence of friction forces the moment of momentum of any fluid particle concerning an axis of an injector remains invariable from an input of an injector before escaping it;

$$w_{вх} R = W_u r, \qquad (3)$$

where $w_{вх}$ — entrance velocity of a liquid in an injector;

R — A radius of gyration of a particle of a liquid on an input in an injector;

r — A radius of gyration of a particle of a liquid in output cross-section of the nozzle.

For perfect fluid current margin of energy in a flow does not change and determined by a Bernoulli's relation

$$p_{вх} + \frac{\rho w_{вх}^2}{2} = p + \rho\frac{W_u^2}{2} + \rho\frac{W_a^2}{2} = p_ф = const,$$

where $p_{вх}, p$ - static pressure accordingly on an input in the chamber of twisting and on escaping of the nozzle;

ρ — Liquid density;

p_ϕ — total pressure on an input in an injector, or

$$p = p_\phi - \rho\left(\frac{W_u^2}{2} + \frac{W_a^2}{2}\right). \qquad (4)$$

From (3) and (4) formally follows, that near to an axis of an injector (see fig. 3) circumferential component of velocities aims at indefinitely large positive value, and static pressure — to indefinitely large negative pressure that is physically impossible.

Really, the injector supply a liquid to a medium with fixed pressure, equal, for example, to combustion-chamber pressure. The internal cavity of an injector is communicated with a surrounding medium, and pressure of a twisted fluid flow cannot be lower than ambient pressure. Therefore the velocity of a twisted fluid flow increases as approaching an axis of an injector until pressure in a twisted fluid flow will not reach ambient pressure.

The further pressure decrease and increase of a velocity are physically impossible. Hence, the central part of an injector where pressure is equal to ambient pressure, is not completed by a liquid. In this part there is a gas vortex (an overpressure $p_в$ — 0) with radius $r_в$.

The expiration of a liquid happens through ring cross-section

$$F_ж = \pi\left(r_c^2 - r_в^2\right) = \varphi\pi r_c^2, \qquad (5)$$

where $r_в$ — radius of a gas vortex;

$$\varphi = 1 - \frac{r_в^2}{r_c^2} \qquad (6)$$

φ — Space factor of cross-section of a injector nuzzle.

For definition of character of distribution of axial component of velocity W_a in output cross-section of the nozzle we shall take advantage of a d'Alembert principle. According to this principle, a pressure differential Δp on lateral areas of an elemental annulus (fig. 4) of the twisted flush having radius r and width dr, is equilibrated by an operation of the centrifugal force, at surface of an elemental annulus unit

$$dp = \frac{W_u^2}{r} dm .$$

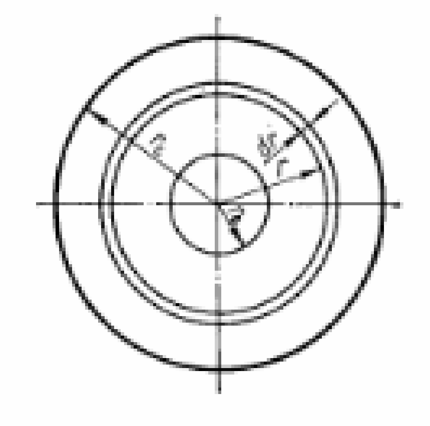


Fig. 4. To calculation of an axial component of velocity

The elemental annulus with a surface, equal unit, has weight

dm=ρdr.

Then

$$dp = \rho W_u^2 \frac{dr}{r} .$$

Differentiating on r an equation (3), we have

$$\frac{dr}{r} = -\frac{dW_u}{W_u} ,$$

whence

$$dp = -\rho W_u dW_u .$$

After an integration, we shall receive

$$p + \frac{\rho W_u^2}{2} = const . \qquad (7)$$

Using a requirement, on which on the boundary of a gas vortex tangential component velocities

$W_u = W_{uв}$,

and an overpressure

$p = p_в = 0$,

let's discover value of constants of integration:

$$const = \rho \frac{W_{uв}^2}{2}. \qquad (8)$$

Using (7) and (8), we shall receive the partition law of pressure ensuring equilibrium of a twisted fluid flow:

$$p = \rho \frac{W_{uв}^2}{2} - \rho \frac{W_u^2}{2}. \qquad (9)$$

Comparing (4) and (9), we discover, that an axial component of a velocity in output cross-section of the nozzle is a stationary value:

$$W_a = const. \qquad (10)$$

The value of an axial component velocity can be found from (4) and (9):

$$W_a = \sqrt{2\frac{p_ф}{\rho} - W_{uв}^2}. \qquad (11)$$

Ratio obtained above allow to deduce design formulas for definition of a flow rate coefficient and a angle of atomization of liquids in a centrifugal injector and to establish the parameters influencing them.

In a a centrifugal injector the expiration of a liquid happens through ring cross-section area $F_ж$ with axial component of velocity W_a. The second flow rate of a propellant component

$$Q = F_ж W_a = \varphi \pi r_c^2 W_a. \qquad (12)$$

An equivalent axial velocity we shall understand that fictive exhaust velocity which would receive if the flow rate implemented not through the ring area of injector $F_ж$ and through all cross-sectional area of a injector πr_c^2 i.e.

$$W_э = \frac{Q}{\pi r_c^2}. \quad (13)$$

Using (12) and (13), we shall receive through an equivalent velocity value of an axial component of velocity

$$W_a = \frac{W_э}{\varphi}. \quad (14)$$

Rate of flow on an input

$$Q = W_{вх} \pi r_{вх}^2 \quad (15)$$

where $r_{вх}$ — radius of an input tangential hole of an injector.

From (13) and (15) it is discovered through an equivalent velocity value of entrance velocity of a liquid in an injector:

$$W_{вх} = W_э \frac{r_c^2}{r_{вх}^2}. \quad (16)$$

Using a conservation law of a moment of momentum, it is possible to receive relation of a tangential velocity in any point of a flow from an equivalent velocity. Really, from a conservation law of a moment of momentum follows, that

$$W_u r = W_{вх} R.$$

Using (16), we shall receive

$$W_u = W_э \frac{R}{r} \frac{r_c^2}{r_{вх}^2}. \quad (17)$$

In a similar way we shall receive analogous relations for a tangential velocity about a wall of output cross-section of an injector

$$W_{uc} = W_э R \frac{r_c}{r_в^2} \qquad (18)$$

and a tangential velocity on the boundary with a gas vortex in outlet of an injector

$$W_{uc} = W_э \frac{Rr_c}{r_{вх}^2} \frac{r_c}{r_в},$$

or with the account (8.6)

$$W_{uc} = W_э \frac{Rr_c}{r_{вх}^2} \frac{1}{\sqrt{1-\varphi}} \qquad (19)$$

Using (11), (14), (19), we shall receive through an equivalent velocity an equation for definition of total pressure of a liquid in an injector:

$$p_ф = \frac{\rho W_э^2}{2}\left[\frac{1}{\varphi^2} + \frac{R^2 r_c^2}{r_{вх}^4 (1-\varphi)}\right], \qquad (20)$$

whence

$$W_э = \frac{\sqrt{2\frac{p_ф}{\rho}}}{\sqrt{\frac{1}{\varphi^2} + \frac{A^2}{1-\varphi}}} = \mu_ф \sqrt{2\frac{p_ф}{\rho}}, \qquad (21)$$

where $A = \frac{Rr_c}{r_{вх}^2}$ — the geometrical characteristic of a centrifugal injector.

Taking into account concept about an equivalent velocity, we come to a conclusion, that a flow rate coefficient of an injector is

$$\mu_ф = \frac{1}{\sqrt{\frac{1}{\varphi^2} + \frac{A^2}{1-\varphi}}}. \qquad (22)$$

From (22) it is visible, that the flow rate coefficient is determined by value of the geometrical characteristic and space factor of a injector jet, therefore it is necessary to know the connection between its.

From (22) follows, that depending on the size of a gas vortex (space factor of a injector jet) this or that rate of flow can be established. Calculations display, that both at very large, and at very small sizes of a gas vortex the flow rate coefficient is small.

At increase of the size of a gas vortex the rate of flow through an injector is reduced because of decreasing of space factor of a injector jet. At decreasing of the size of a gas vortex the axial component of a velocity decreases as the power consumption on creation of large radial velocities in the points located near to an axis of the nozzle predominates.

It proved, that the gas vortex ensuring at the given head a peak flow rate of a liquid through an injector, should be steady. Hence, a true value of φ corresponds to minimum value of a function

$$\frac{1}{\varphi^2}+\frac{A^2}{1-\varphi}$$

For definition of an extremum of this function we shall take the first derivative and we shall equate to its null:

$$\frac{d}{d\varphi}\left(\frac{A^2}{1-\varphi}+\frac{1}{\varphi^2}\right)=\frac{A^2}{(1-\varphi)^2}-\frac{2}{\varphi^3}=0\,.$$

The flexon from this function has positive value that indicates presence of a minimum of an examined function. In outcome the following relation between a factor of a free area and the geometrical characteristic of an injector is implemented:

$$A=\frac{1-\varphi}{\sqrt{\frac{\varphi^3}{2}}}\,. \qquad (23)$$

From (23) it is visible, that the geometrical characteristic of an injector uniquely determinates value of φ. Using (22) and (23.) we shall receive a resultant expression for a flow rate coefficient of an injector

$$\mu_ф = \sqrt{\frac{\varphi^3}{2-\varphi}}\,. \qquad (24)$$

The flow coefficient of a injector, as well as space factor of a nozzle, is uniquely determinated by value of the geometrical characteristic and does not depend on operational modes of an injector. It is fair for perfect fluid.

From (23) and (24) follows, that at change of the geometrical characteristic A from 0 up to ∞ , flow coefficient $\mu_ф$ and space factor of the nozzle φ of injector change from 1 up to 0.). Known value of $\mu_ф$, the flow rate through a centrifugal injector on (1) is definable.

Other important characteristic of a swirl-type burner — a an angle of an atomization of a liquid. The tangent of a lateral angle of an atomization of a liquid is determined on (2).

Whereas in output cross-section of the nozzle the axial component of velocity W_a = const, and circumferential component W_u is increased as approaching an axis of an injector, an angle of an atomization of the particles located on different radiuses r from an axis of an injector, is unequal.

Angle of an atomization of the particles located closer to an axis of an injector, more, than at particles, more remote from an axis of an injector. At calculation of an angle of an atomization of a liquid receive some mean angle of an atomization relevant to mean radial velocity:

$$\text{tg}\overline{\alpha} = \frac{W_{uср}}{W_a}, \qquad (25)$$

где $W_{uср} = W_{uс}\dfrac{r_с}{r_{ср}}$,

$r_{ср} = \dfrac{r_с + r_в}{2}$ — Mean radius.

Using (6), (18) and (23), we shall receive the formula for calculation of angle of atomization of a propellant component:

$$\mathrm{tg}\overline{\alpha} = (1-\varphi)\frac{\sqrt{8}}{\left(1+\sqrt{1-\varphi}\right)\sqrt{\varphi}}\,. \qquad (26)$$

From (26) it is visible, that the angle of an atomization for perfect fluid is uniquely determinated by the geometrical characteristic of an injector and does not depend on a mode of its activity. It is necessary to mark, that the equation (26) yields the overstated values of a an angle of an atomization of a liquid as at its conclusion increasing of a radial pressure of a liquid from an operation of centrifugal forces was not taken into account.

Really, pressure on a shear of a injector nuzzle should be to stationary values and equal to combustion-chamber pressure. Exuberant centrifugal pressure in a cylindrical part of an injector will be transformed to kinetic head. It conducts to increasing of axial component of velocity W_a and decreasing of a an angle of an atomization of propellant, andat the wall of nuzzle W_a is greater, than on the boundary of a gas vortex.

At incompressible liquid the axial component of a velocity can increas only at the expense of decreasing of a free area of a flow. Therefore the radius of a gas vortex is more on escaping of the nozzle, than in depth of the chamber of twisting.

Let's discover distribution axial component and radius of a gas vortex in output cross-section of an injector nuzzle. Taking into account, that the overpressure on a shear of an injector nuzzle is equal to null, from an equation (4) follows (a radial component velocity is neglected), that

$$W_a^2 + W_u^2 = 2\frac{p_\phi}{\rho}\,. \qquad (27)$$

From a conservation law of a moment of momentum

$$W_u = \frac{R}{r} W_{вх}\,.$$

Taking into account, that volume-flow through an injector

$$Q = \mu_\phi \pi r_c^2 \sqrt{2\frac{p_\phi}{\rho}},$$

let's receive

$$W_u = A\mu_\phi \frac{r_c}{r}\sqrt{2\frac{p_\phi}{\rho}}. \qquad (28)$$

Having substituted value W_u in (27), we shall discover distribution of an axial component of velocity on a shear of the nozzle:

$$W_a = \sqrt{1-\frac{\mu_\phi^2 A^2 r_c^2}{r^2}}\sqrt{2\frac{p_\phi}{\rho}}. \qquad (29)$$

From (29) follows, that with increase of distance from an axis of the nozzle the axial component of a velocity grows and reaches maximum value at walls of the nozzle.

The radius of a gas vortex on escaping of an injector nozzle can be determined from volume-flow of a liquid if to write it as an integral from elementary flow rate on a shear of the nozzle:

$$Q = \int_{r_{\text{цв}}}^{r_c} W_a\, 2\pi r dr = \pi r_c^2 \mu_\phi \sqrt{2\frac{p_\phi}{\rho}}.$$

Using W_a from (29) and having executed an integration, we shall receive the transcendental expression for definition $r_{\text{вс}}$:

$$\mu_\phi = \sqrt{1-\mu_\phi^2 A^2} - S\sqrt{S^2-\mu_\phi^2 A^2} - \mu_\phi^2 A^2 \ln\left(\frac{1+\sqrt{1-\mu_\phi^2 A^2}}{S+\sqrt{S^2-\mu_\phi^2 A^2}}\right) (30)$$

where $S = \frac{r_{\text{вс}}}{r_c}$ — dimensionless radius of a vortex on a shear of the nozzle.

Connection between μ_ϕ and A it is determined by equations (23) and (24).

Deciding graphically an equation (30), we discover relation 1 (fig. 5) of dimensionless radius of a vortex on a shear of the nozzle, and also relation of dimensionless radius of a vortex in the beginning of the nozzle 2 and on a back wall of the chamber of twisting 3 from the geometrical characteristic.

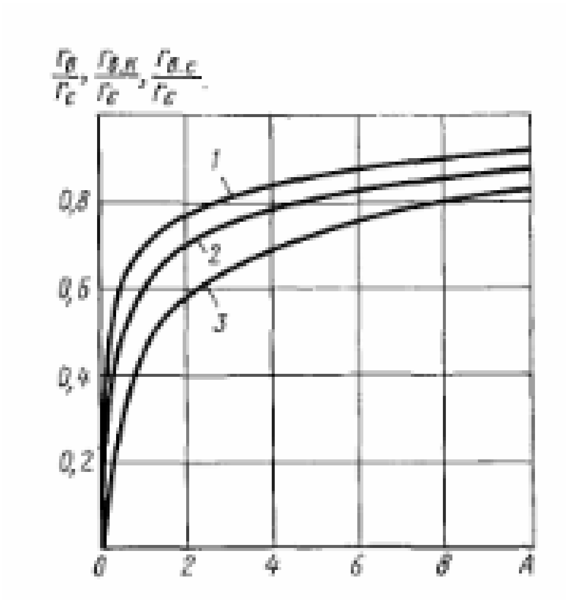


Fig. 5.Radius of a gas whirlwind to the injector geometrical characteristic

Angle of a plume of the sputtered liquid, as it was indicated, determined by the relation of tangent and axial making speed. This relation differs on nozzle section, therefore for calculations average value of spraying angle is entered

$$tg\bar{\alpha} = \frac{\overline{W}_u}{\overline{W}_a}$$

As average values $\overline{W}_u$ и $\overline{W}_a$, let's accept their values on radius:

$$\bar{r} = \frac{r_c + r_{вс}}{2} = r_c \frac{1+S}{2}.$$

From expressions (28) and (20) average values are

$$\overline{W}_u = \frac{2\mu_\phi A}{1+S}\sqrt{\frac{2p_\phi}{\rho}};$$

$$\overline{W}_a = \sqrt{1-\frac{4\mu_\phi^2 A^2}{(1+S)^2}}\sqrt{\frac{2p_\phi}{\rho}}.$$

Then

$$\mathrm{tg}\overline{\alpha} = \frac{2\mu_\phi A}{\sqrt{(1+S)^2 - 4\mu_\phi^2 A^2}}. \qquad (31)$$

In drawing 6 flow coefficient μ_ϕ change, an angle $2\overline{\alpha}$ of a atomization of liquid and factor of flow section φ a centrifugal injector depending on value of the injector geometrical characteristic is presented.

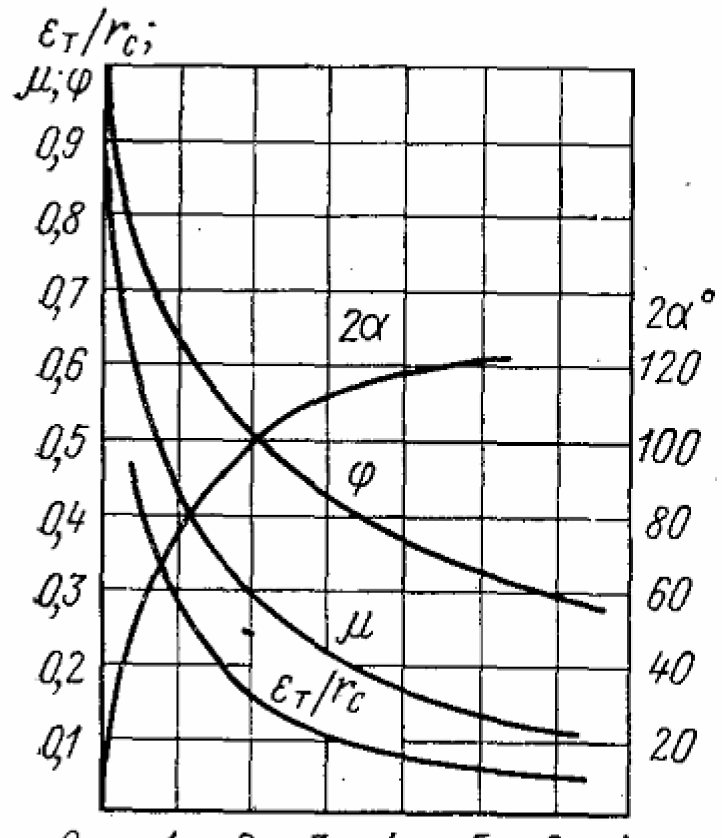


Fig. 6. Relation of an injector angle, a flow coefficient and factor of flow section of a stream of a centrifugal injector from the geometrical characteristic of an injector

Quality of an atomisation essentially depends on a thickness $\varepsilon_т$ of a sheet of the fuel, following of an injector taken on a normal to velocity vector of a liquid:

$$\varepsilon_т = (r_c - r_в)\cos\alpha .$$

The sheet, following from the nozzle of an injector is unstable to effect of weak disturbances (a roughness of walls, turbulent oscillations in a liquid etc.). On a sheet the longitudinal and cross-section waves which amplitudes fast grow are formed. From ridges of waves the smallest drops break, and then and all sheet breaks up to a spectrum of drops of various diameters.

On a surface of a drop, moving in relation to gas, there is a distribution of pressure which deforms, flattens a drop. At a certain ratio of parametres, force of aerodynamic pressure can overcome forces of surface tension, and there will be a drop split. The relation of the indicated forces name criterion of split or Veber criterion:

$$D = \rho_г W^2 a / \sigma ,$$

Where *a* - diameter of a drop; W its speed in relation to gas with density $\rho_г$; σ - factor of surface tension of a drop.

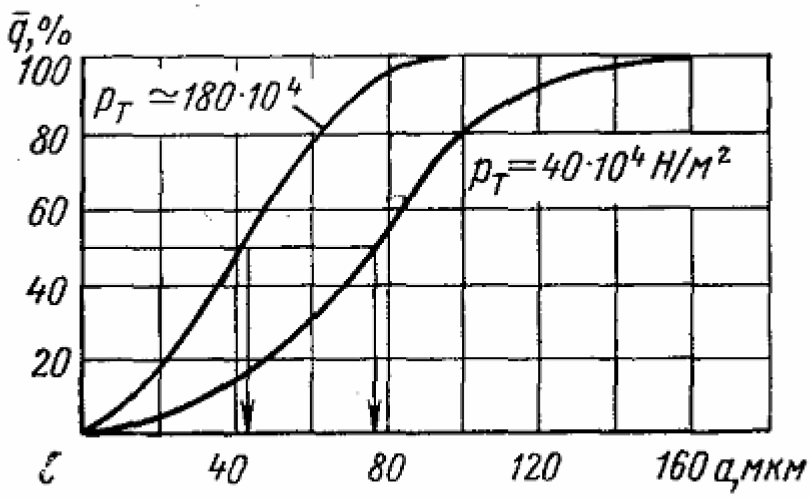
At D=14 the split ceiling when all of 100 % of drops are split up for set of smaller drops is reached.

Split of drops leads to substantial growth of their general surface that increases fuel evaporation, and formation of a fresh mix.

After end of the split process plenty of drops of various diameters are formed.

The experimental methods are developed, allowing to determine quantity and weight of drops with dimension *Gi*, for example, from 0 to 20 microns, from 20 to 40 microns etc.

Spray spectra are constructed by the experimental data. On fig. as an example of spray spectra for an centrifugal injector are shown at pressure of an atomisation $180 \cdot 10^4$and $40 \cdot 10^4$ Н/м^2.



For maintenance of more uniform propellant flow rate on perimeter of cone of atomization, instead of one tangential aperture usually there are some. Then the geometrical characteristic for n apertures is

$$A = \frac{Rr_c}{nr_{вх}^2}. \qquad (32)$$

If between a direction of an axis of an entrance aperture and a nozzle axis there is an angle,β then

$$A = \frac{Rr_c}{nr_{вх}^2}\sin\beta. \qquad (33)$$

Generally, when the entrance aperture has no a circle form in cross-section,

$$A = \frac{Rr_c\pi}{nf_{вх}}\sin\beta. \qquad (34)$$

Where $f_{вх}$— the area of the channel.

In case of feed screw using (fig. 1) for flow twist, all ratios received for a centrifugal injector, also will be usefull, thus

$$A = \frac{\pi d_3 d_c}{4if_i}, \qquad (35)$$

Where d_3, — average diameter;

i — passes number of a thread feed screw;

f_i —The section area of one channel through feed screw passage.

The moment for an ideal liquid remains invariable for all hydraulic channel of a liquid, and all hydraulic characteristics are unequivocally determined by the geometrical characteristic. The real liquid has certain viscosity.

THE THEORY AND CALCULATION OF CENTRIFUGAL INJECTOR WITH TAKING INTO ACCOUNT VISCOSITY OF PROPELLANT COMPONENTS

Owing to viscosity of a liquid on a wall, there are the forces of a friction directed towards to flow rate. The moment of a friction forces involves reduction of the moment of momentum. As a result, the momentum moment on an input in the nozzle is less, than on an input in the twisting chamber. With reduction of the moment of momentum the radius of a gas whirlwind and an angle spray of a liquid are unexpected at first sight result - to increasing of a flow coefficient of a liquid mass flow.

Implementation of an injector equivalent geometrical characteristic is the way for take in to the account of viscosity.

By analogy to an ideal liquid the formula for a flow coefficient of a viscous liquid looks like:

$$\mu_{\phi} = \frac{1}{\sqrt{\frac{A_э^2}{1-\varphi} + \frac{1}{\varphi^2}}}, \qquad (36)$$

Where the equivalent geometrical characteristic of an injector

$$A_э = \frac{A}{1 + \frac{\lambda}{2}\left(\frac{B^2}{n} - A\right)}. \qquad (37)$$

λ — Friction factor;

$B = \frac{R}{r_{вх}}$;

R – a twisting shoulder;

n – number of entrance apertures.

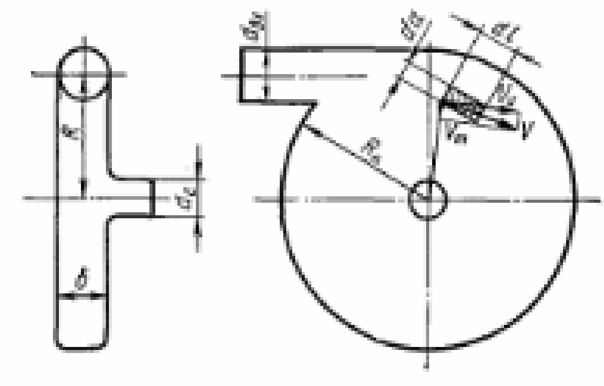


Fig. 7. Decomposition of flow rate of a liquid in chamber on components

Friction factor

$$\lg\lambda = \frac{25{,}8}{(\lg \mathrm{Re})^{2{,}58}} - 2$$

From a condition on an input in the twisting chamber determine number Re.

$$\mathrm{Re} = \frac{W_{вх} d}{\nu_{ж}},$$

where $d = \sqrt{n} d_{вх}$;

$\nu_{ж}$ —Factor of kinematic viscosity of a liquid.

Taking into accountthe continuity equation

$$\mathrm{Re} = \frac{4\dot{m}_{ф}}{\pi\rho_{ж}\nu_{ж}\sqrt{n} d_{вх}}$$

Functional connection between φ and $A_э$, is determined the same as and for an ideal injector.

$$A_э = (1-\varphi)\frac{\sqrt{2}}{\sqrt{\varphi^3}}$$

The formula for definition of angle of atomization has the same appearance (31), as for an ideal liquid:

$$\mathrm{tg}\overline{\alpha} = \frac{2\mu_{ф} A_э}{\sqrt{(1+S)^2 - 4\mu_{ф} A_э^2}}$$

Here it is necessary in the formula instead of the geometrical characteristic of an injector to substitute the equivalent geometrical characteristic of an injector. Thus, the formula for calculation $\mu_ф$ and α taking into account viscosity differs from the corresponding formula for an ideal liquid only replacement A on $A_э$. Therefore it is possible to use earlier constructed relations (fig. 6), only it is necessary to take value $A_э$ instead of A.

The equivalent geometrical characteristic considers reduction of the moment of momentum in the twisting chamber. As $A_э < A$, the corner of liquid atomization is less, and the flow coefficient is more for a viscous liquid in comparison with the ideal.

Unlike an ideal liquid the equivalent characteristic remains in final value for a real liquid. Maximum final value of $A_э$ depends only on a way of change of geometrical characteristics due to increase R or reduction $r_{вх}$.

Hence, the flow coefficient cannot be less, and a corner more than quite certain value determined by the maximum value of the equivalent geometrical characteristic for a real liquid.

The increasing of corner of fuel atomization due to reduction of entrance channels is limited by technological and operational difficulties (manufacturing complexity of apertures of small diameter, danger of their clogging). It is possible to increase an atomization corner as a result of decrease of a friction by increasing of a class of cleanliness of manufacturing or a fuel heating that is not always possible and was expediently to execute for constructive, technological or operational reasons.

CALCULATIONS WIRL-TYPE INJECTOR WITH EXTERNAL AND INTERNAL MIXTURE OF PROPELLANT COMPONENTS

Doublet injectors (fig. 8) happen with external (a) and internal (б) mixture.

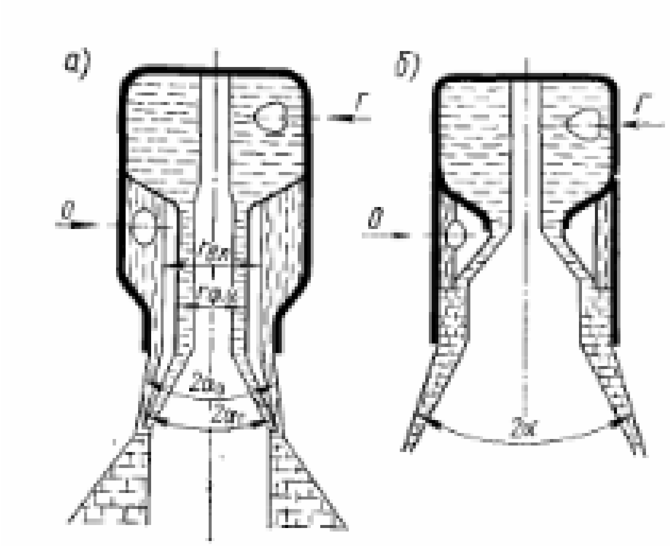


Fig. 8. The Doublet injector

Doublet injectors with external mixture have two chambers of a twisting. Parameters of injectors should be picked up so that cones of an atomization of fuel $2\alpha_г$ and oxidizers $2\alpha_0$ were crossed close to an exit. In a doublet injector with internal mixture process of interaction of fuel and oxidizers begins inside an injector. As a result fuel preliminary hashed in the necessary ratio follows from an injector. Use of doublet injectors improves mixing process, allows to burn propellant at small volumes chamber with high completeness of combustion.

Calculation of a doublet injector with external mixture differs nothing from calculation of single-component swirl-type injector. It is necessary to be convinced only, that radius of a gas whirlwind of a outer injector more than outside radius of a central nozzle i.e.

$$r_{вп} \triangleright r_{фц}. \qquad (38)$$

Knowing the geometrical characteristic of a outer injector, we find $r_в$, under the schedule represented on fig.5, and we check up fulfillment of an inequality (38). It is necessary to redesign an injector or to make on interaction of a fluid flow with a wall of central injectors in case of inequality non-observance.

Let's calculate a bicomponent swirl-type injector for ideal liquid. Its computational scheme is presented on fig. 9

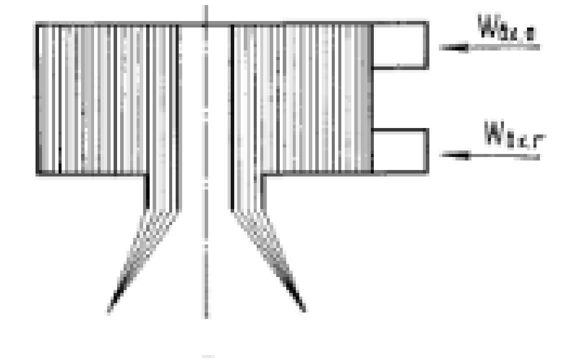


Fig. 9. The computational scheme of bicomponent swirl-type injector with internal mixture

Let's put, that fuel and an oxidizer move in the combustion chamber under the same pressure differential. Then, considering, that entrance channels of injectors are informed with the general chamber of a twisting, we will record

$$p_{фг} + \frac{\rho_г W_{вхг}^2}{2} = p_{фо} + \frac{\rho_{фо} W_{вхо}^2}{2}. \qquad (39)$$

From (39) follows

$$W_{вхг} = W_{вхо}\sqrt{\frac{\rho_о}{\rho_г}}. \qquad (40)$$

Mass components ratio of propellant in each injector

$$\kappa_m = \frac{\dot{m}_{фо}}{\dot{m}_{фг}} = \frac{d_{вхо}^2}{d_{вхг}^2}\frac{n_о}{n_г}\frac{\rho_о}{\rho_г}\frac{W_{вхо}}{W_{вхг}}, \text{ or}$$

$$\kappa_m = \sqrt{\frac{\rho_о}{\rho_г}}\frac{n_о d_{вхо}^2}{n_г d_{вхг}^2} \qquad (41).$$

Here $\dot{m}_{фо}$ and $\dot{m}_{фг}$ —mass flow of an oxidizer and fuel through an injector accordingly.

Total mass flow through an injector

$$\dot{m}_ф = \dot{m}_{фо} + \dot{m}_{фг} = \frac{\kappa_m + 1}{\kappa_m}\dot{m}_{фо} = \frac{\kappa_m + 1}{\kappa_m} n_о \pi r_{вхо}^2 W_{вхо} \rho_о,$$

or

$$\dot{m}_ф = n_о \pi \bar{r}_{вх}^2 W_{вхо} \rho_о, \qquad (42)$$

where

$$\bar{r}_{вх} = r_{вхо}\sqrt{\frac{\kappa_m + 1}{\kappa_m}}.$$

From the law of preservation of momentum, neglecting power losses at mixture, follows, that

$$\dot{m}_ф R W_{вх} = \dot{m}_{фо} R W_{вхо} + \dot{m}_{вхг} R W_{вхг} \cos\beta,$$

where β — a corner of an inclination of an entrance fuel passage to a plane, a perpendicular axis of an injector.

From here

$$W_{вх} = \frac{\dot{m}_{фо} W_{вхо} + \dot{m}_{вхг} W_{вхг} \cos\beta}{\dot{m}_ф},$$

or, using (40), after transformations

$$W_{вх} = W_{вхо}\kappa_m \left(1 + \sqrt{\rho_о/\rho_г}\cos\beta/\kappa_m\right)/(\kappa_m + 1).$$

Let's designate

$$\overline{R} = R\kappa_m \left(1 + \sqrt{\rho_о/\rho_г}\cos\beta/\kappa_m\right)/(\kappa_m + 1).$$

Then the moment of momentum of 1kg of propellant

$$M = RW_{вх} = \overline{R}W_{вхо}. \qquad (43)$$

Using (42) and (43) and having made similar transformations, as for an ideal swirl-type injector, we will receive expression of the geometrical characteristic for bicomponental swirl-type injector:

$$\overline{A} = \frac{\kappa_m\left(\kappa_m + \sqrt{\rho_о/\rho_г}\cos\beta\right)}{(\kappa_m + 1)(\kappa_m + \rho_о/\rho_г)}\frac{Rr_c}{n_о r_{вхо}^2}$$

where $\overline{A}$ — the geometrical characteristic of a doublet injector with internal mixture.

It is necessary to notice, that relations of $\mu_ф$, φ, $2\overline{\alpha}$ from $\overline{A}$ remains same, as well as for a monopropellant injector. Only it is necessary to take value of the geometrical characteristic of doublet injector $\overline{A}$ instead of the geometrical characteristic of an injector A. Then mass flow of propellant

$$\dot{m}_ф = \mu_ф F_{сф}\sqrt{2\rho_т \Delta p_ф},$$

where

$$\rho_т = \frac{\rho_о \rho_г (1 + \kappa_m)}{\rho_о + \kappa_m \rho_г}$$ - specific density of propellant.

Doublet injectors are designed often with a large deployment of the nozzle that is characterised by relation R/r_c. It is necessary to enter the correction if relation R/rc <3. The relation of experimental value of a flow coefficient to its computational value depending on R/rc is resulted on fig. 10. It allows making the corresponding correction to results of calculation.

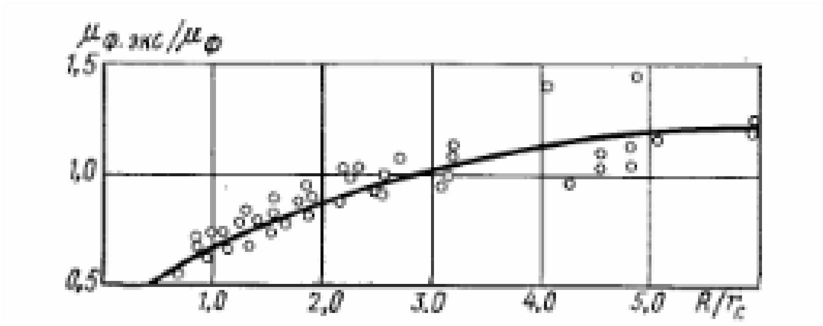


Fig. 10. Experimental relation $\mu_{фэкс} / \mu_ф = f(R / r_c)$