# INFLUENCE OF LRE MODEL INJECTOR GEOMETRY ON EXCITATION OF TRANSVERSE GAS OSCILLATIONS IN THE COMBUSTION CHAMBER

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Interest in the study of oscillatory combustion in various types of burners has increased markedly with the development and advancements in the field of missile and aviation technology [1-3]. Increase of the thermal loading of the liquid rocket engine (LRE) has been achieved by increasing the combustion chamber diameter and reducing its length. This has led to the appearance in the combustion chamber of transverse gas oscillations that are large in magnitude and can damage the hardware [4]. Extensive developmental studies have been required for each newly created engine, and experience in the development of one engine can not always be used in developing another. A particularly large number of problems has arisen in assuring stable combustion in developing engines when at least one of the propellant components is supplied to the combustion chamber in the gaseous state through axial channels. As a rule, in full-scale LRE combustion chambers the channel diameter selection is determined by the mixture formation scheme and by the combustion chamber dimensions [4]. This selection is basically associated with assuring high combustion efficiency, i.e., with the length of the burning zone.

The need for modeling of this process arose because of the cost of the studies on the full-scale engines. The advantages of the model studies are obvious: lower material expenditures, the ease of obtaining a large volume of information, the possibility of studying the whole series of physical and operating regime parameters influencing the conditions of transverse gas oscillation excitation. One of the most successful techniques for modeling the process of the excitation of acoustic (transverse mode) gas oscillations in full-scale LRE combustion chambers is the test technique described in [5]. The essence of this technique is the burning of a premixed (homogeneous) combustible mixture of gasoline and air at approximately atmospheric pressure in a combustion chamber of simplified construction. An advantage of this technique is the elimination from consideration of certain processes (atomization, intermixing, and vaporization of the propellant components) that can in themselves influence the conditions of the excitation of gas oscillations in the combustion chamber. The influence of a whole series of combustion chamber physical and operating regime parameters on the conditions of transverse gas oscillation excitation was identified. Qualitative agreement of the results of model and full-scale tests was obtained.

It is well known from [2, 6-8] that in many cases a radical means for suppression of the acoustic oscillations in a particular burner is the use of special acoustic absorbers, which can be installed either inside or outside of the combustion chamber. However, their installation on full-scale engines significantly complicates the construction of the combustion chamber. Promising for the suppression of oscillatory combustion is the possibility of the use for these purposes of certain physical parameters of the injector head without any significant changes in the construction of the combustion chamber. According to the available literature sources, independent influence of any particular physical parameter of the injector head on the suppression of the transverse oscillations has not been found. As a rule, change of one physical parameter of the head has been accompanied by change of the other parameters, also influencing the stability of the combustion process.

The present work is devoted to an experimental study of the influence of the physical parameters of the combustion chamber injector head on the stability of the combustion process relative to transverse gas oscillations in the main chamber. The following were identified as the independent parameters to be studied: the length, diameter, and form of conicity of the gas channels, and the permeability of the injector head with invariability of the other physical and operating regime parameters.

**1. Experimental Model and Test Technique.** The experiments were performed on a combustion chamber with a cylindrical segment of diameter 280 mm, a schematic of which is shown in Fig. 1. The chamber was a welded structure of

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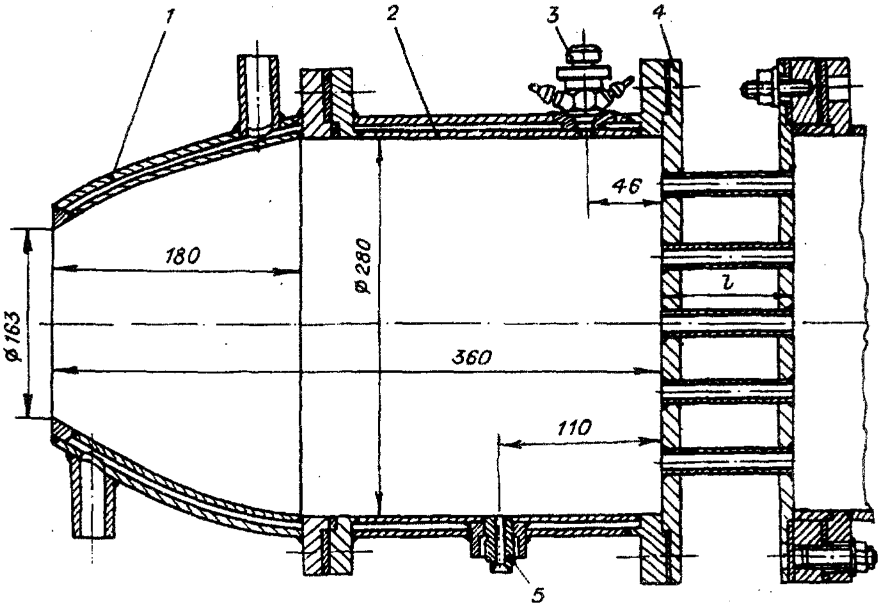

Fig. 1

1Kh18N9T stainless steel and consisted of the following primary parts: the cylindrical segment 2, the profiled nozzle 1, and the injector head 4. The cylindrical segment and the nozzle were water cooled. The injector head was also a welded structure of 1Kh18N9T steel, consisting of two endplates and tubes (gas channels) installed in them. The tube wall thickness was 1 mm.

In the case of the experiments associated with determining the influence of the length of the gas channels and the permeability of the injector head, the channel length $l_g$ was varied from 6 to 250 mm; in the experiments we used heads with permeability $\bar{f} = 0.134$ and 0.255 (respectively 73 and 139 holes in a honeycomb arrangement with spacing between the holes 30 and 22 mm). The head permeability is the ratio of the overall area of the gas channels in the head to the cross section area of the cylindrical part of the chamber.

In the experiments with cylindrical channels of differing diameter, their inner diameters were 6, 12, 18.4, and 23.5 mm. The channel length was also varied from 6 to 120 mm. The number of channels in the head varied, depending on the diameter of the channels, which were arranged in a honeycomb pattern. Thus, in the heads with channel diameter 6 mm there were 283 holes (15 mm spacing between the holes), in the heads with channel diameter 12 mm there were 73 holes (spacing 30 mm), in the heads with channel diameter 18.4 mm there were 31 holes (spacing 44 mm), and in the heads with channel diameter 23.5 mm there were 19 holes (spacing 56 mm).

In the experiments with the injector heads in which there were installed gas channels of diverging ($\varphi = 3$ and 5°) and converging ($\varphi = 3$, 5, and 10°) form, we varied both the length and initial diameter of the gas channels and the head permeability, based on the larger channel diameter. In all cases the smaller diameter of the channels was 12 mm.

To obtain a homogeneous mixture, the liquid fuel (B-70 gasoline) was sprayed into a stream of heated air. A manifold with centrifugal injectors was located at a distance of 8 mm from the combustion chamber diffusor in a thermally insulated tube of diameter 150 mm, where vaporization of the fuel and intermixing of its vapors with the air took place. The air, coming from a compressor, was heated in a heat exchanger. The temperature of the mixture entering the combustion chamber was maintained approximately constant and equal to 473 K (with deviation of up to 10 K in some cases). The air flowrate was measured with a metering orifice (standard nozzle), the fuel flowrate was measured with the aid of a rotameter that was calibrated using a fuel consumption meter. The static pressure $p_c$ in the chamber was measured by the sensor 5 at a distance of 110 mm from the injector head and varied from 100 to 200 kPa. The temperatures of the air and the combustible mixture were measured by chromel-copel thermocouples, connected with type PGU galvanometers. The combustible mixture was ignited by an igniter plug. The igniter was turned off after startup of the chamber. The oscillations of the pressure in the chamber were recorded with the aid of type DDTA-2 strain gauge sensors (the static characteristic was linear up to 300 kPa). The signal from the strain gauge sensor was fed to a model UTS-12/35 strain gauge controller, from which the established signal was fed through a filter to a model S1-16 cathode oscillograph. The oscillograph screen was photographed onto fluorographic film by means of a Zorkii-6 camera.

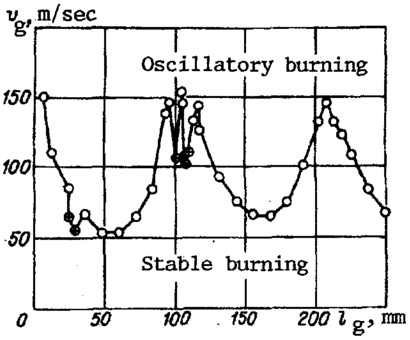

Fig. 2

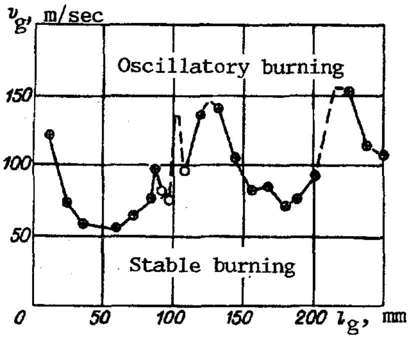

Fig. 3

As a rule, two strain gauge sensors 3 were installed on the cylindrical segment of the combustion chamber in the immediate vicinity of the injector head (at a distance of 46 mm), diametrically opposite one another. A third sensor was located along the generator of one of the sensors of the section noted above. In the experiment we noted coincidence of the phase of the oscillations that were recorded by the sensors installed on the same generator, and a shift in the phase by a halfperiod (antiphase) for the sensors that were installed opposite one another in the first section, i.e., tangential oscillations of the gas in the combustion chamber were recorded. For the specific conditions of the experiment, the frequency of these oscillations was $\nu$ = 1.8 to 2.1 kHz, which corresponded to the fundamental tone of the tangential oscillations.

In the experiments we determined the limits of the oscillatory combustion region in the coordinates: combustible mixture flowrate G vs excess air ratio $\alpha$. The oscillatory combustion region limit was determined as follows. At a certain air flowrate we increased the fuel flowrate until oscillations appeared, and then we increased it further if possible until these oscillations disappeared. If oscillations did not arise at the given air flowrate, the latter was increased and the fuel flowrate was again increased, and so on. Recording of the presence or absence of the oscillations was performed with the aid of the strain gauges. The onset of oscillatory combustion was also observed on the basis of change of the section of the flame downstream of the nozzle. The error in determining the position of the oscillatory combustion region limit based on the combustible mixture flowrate did not exceed 5%.

**2. Experimental Results.** Figures 2 and 3 show the data from reduction of the experimental results for the injector heads of permeability $\bar{f}$ = 0.134 and 0.255 respectively. The ordinates are the values of the section-average combustible mixture flow velocity $v_g$ in the injector head gas channels at which tangential oscillations were excited at the oscillatory combustion region limit with $\alpha \approx 1$ (when the conditions for gas oscillation excitation are maximal), while the abscissas are the lengths $l_g$ of the gas channels of the injector heads being studied.

We see from Figs. 2 and 3 that the installation of injector heads with different length of the gas channels leads to significant change in the mixture flow velocity at which oscillatory combustion arises. The minimal mixture flow velocity at the lower (based on $v_g$) oscillatory combustion region limit for the same channel length is practically the same for the heads with both $\bar{f}$ = 0.134 and $\bar{f}$ = 0.255. We note that for the heads with $\bar{f}$ = 0.255 (Fig. 3) in several cases the limits of the oscillatory combustion region were not obtained because of several factors, including reaching the limiting capabilities of the test stand. The achieved values of the mixture flow velocity are connected with a dashed line.

We see from Figs. 2 and 3 that in the studied range of channel lengths there are two clearly defined stability minima – at $l_g$ = 48 to 62 mm and 156 to 169 mm. We also note another minimum at $l_g$ = 250 mm. Stability maxima are clearly seen at $l_g$ = 6 to 12, 100 to 120, and 210 mm.

It is well known that, other conditions being the same, the acoustic properties of tubes are determined by the ratio of the channel length to the sound wavelength $\lambda_g$ (for the medium in the gas channels $\lambda_g = c_g/\nu$, where $c_g$ is the speed of sound in the channels, $\nu$ is the frequency of the oscillations). In our experiments, we basically recorded a frequency which coincided with one of the natural frequencies of the transverse oscillations of the gas in the combustion chamber $\nu = \alpha_{mn}c_c/d_c$ [9, 10], where $c_c$ is the isentropic speed of sound in the main chamber, $d_c$ is the chamber diameter, $\alpha_{mn}$ is the m-th root of $J_n$ – the Bessel function of the first kind (for the fundamental tone of the tangential oscillations $\alpha_{10}$ = 0.5861). The speed of sound $c_c$ was determined at the temperature of the combustion products with combustion efficiency equal to 100%. For the studied combustion chamber with the cylindrical segment of diameter 280 mm with excess air ratio $\alpha \approx 1$ the frequency of the fundamental tone of the tangential oscillations of the gas was 1.96 kHz.

Figure 4 presents the experimental data on the stability of burning as a function of the Mach number M (ratio of the average flow velocity in the gas channels to the magnitude of the speed of sound in these channels) and the ratio of the length

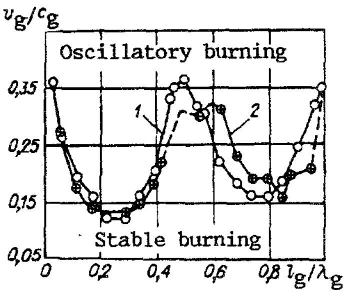

Fig. 4

of the injector head gas channels to the sound wavelength $\lambda_g$ for the medium in these channels (for the fundamental tone of the oscillations in these experiments with $T = 473$ K, $l_g = 212$ mm). Here the line 1 corresponds to the conditions of Fig. 2, while the line 2 corresponds to the conditions of Fig. 3.

We see from Fig. 4 that the minima and maxima are separated from one another by a distance approximately equal to $0.5 l_g/\lambda_g$. This relationship is one of the basic conclusions of the present work and can be used in combustion chamber design. This relationship indicates the acoustic nature of the influence of the length of the gas channels.

We note that in reducing the experimental results we did not consider the fact that the natural frequencies of the longitudinal oscillations of the gas in the injector head channels may vary as a function of the flow velocity. In accordance with [9], the sought frequency of the natural oscillations of the gas can be determined from the simple relation $\nu_p = \nu_0/(1 - M^2)$ ($\nu_p$ and $\nu_0$ are the oscillation frequencies with and without correction for the mixture flow velocity). For most of the experiments the combustible mixture flow velocity was from 40 to 150 m/sec, therefore the correction of the frequency for the velocity in the indicated limits would be from 1 to 15 %. However, in the cited experiments no particular differences in the magnitude of the frequencies of the oscillations were noted.

We should also note that in all the figures presented herein the length of the gas channels was taken to be the physical length, i.e., without the corrections that could be considered in selecting the effective length of the injector head channels [9, 11, 12]. The validity of accounting for such finite corrections for the gas channels of the injector head for full-scale or model LRE chambers has not been proved, and we see from the experimental data presented above that the acoustic properties of the gas channels are quite satisfactorily described by the channel physical length.

It is also known that the relative length of the channel influences the form of the gas flow velocity profile in the channel cross-section, which, generally speaking, could influence the position of the oscillatory burning region limit. The experiments performed showed that with change of the channel length from 60 to 106 mm the velocity profiles in the exit section of the channels were characteristic for fully developed turbulent flow. For the channels of length 12 and 24 mm the boundary layers from the walls did not merge. However, the form of the curves in Figs. 2 and 3 in the compared channel length ranges $6 \text{ mm} < l_g < 96$ mm and $110 \text{ mm} < l_g < 210$ mm indicates that change of the velocity profile has practically no influence on the limits of the oscillatory burning region and that in these experiments the dominating role is that of the change of the acoustic properties of the head with variation of the length of the channels.

We note that in the experiments (see Figs. 2 and 3), in addition to the fundamental tone of the tangential oscillations ($\nu = 1.8$ to $2.1$ kHz), there were also recorded oscillations of the first overtone of these tangential oscillations with frequency $\nu = 2.7$ to $3.1$ kHz in the channel length intervals 28 to 32 and 95 to 115 mm (points ⊗ in Fig. 2 and ○ in Fig. 3). The amplitude of these oscillations was significantly lower than for the fundamental tone. They were typically detected for the channel lengths which had a much worse ratio $l_g/\lambda_g$ than for the fundamental tone, i.e., $l_g/\lambda_g \approx 0.25$ and $0.75$, where the sound wavelength $\lambda_g$ was determined on the basis of the frequency of the first overtone of the tangential oscillations. Thus, the acoustic interaction of the combustion chamber oscillation frequencies with the gas channel frequencies is most favorable for the long channels, in the limits of which there fits a multiple number of halfwaves, at the frequency of the tangential oscillations that are excited in the chamber.

Thus, all the obtained experimental data can be represented as follows. The poorest stability of the combustion process is observed with $l_g/\lambda_g = 0.25k$ ($k = 1, 3, 5, \ldots$), while the best stability is observed with $l_g/\lambda_g = 0.5p$ ($p = 1, 2, 3, \ldots$). Expressing the sound wavelength $\lambda_g$ for the medium of the gas channels of the injector head through the speed of sound and the frequency of the tangential gas oscillations arising in the combustion chamber ($\lambda_g = c_g/\nu$), we find that the poorest stability of the combustion process is provided with

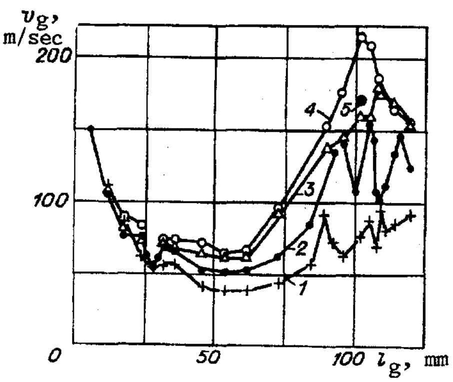

Fig. 5

$$\frac{l_g}{D_c} = 0{,}25\,\frac{k}{\alpha_{mn}}\,\frac{c_g}{c_c} \quad (k = 1, 3, 5, \ldots),$$

and the best stability is provided with

$$\frac{l_g}{D_c} = 0{,}5\,\frac{p}{\alpha_{mn}}\,\frac{c_g}{c_c} \quad (p = 1, 2, 3, \ldots).$$

Figure 5 presents the dependence of the combustible mixture flow velocity at the oscillatory combustion region limit with $\alpha \approx 1$ on the length of the gas channels with differing channel diameter (the channels of diameter 6, 12, 18.4, and 23.5 mm are denoted respectively by the numerals 1-4). The permeability of the injector heads was invariable ($\bar{f} = 0.134$). We see that increase of the channel diameter has a favorable influence on the position of the limit of the oscillatory combustion region. This shows up most clearly for the channel length 100 to 110 mm, i.e., just as in the experiments with the channels of diameter 12 mm (see Fig. 2). The poorest stability of the combustion process is observed in testing the injector heads with channels of length $l_g \approx 0.25\lambda_g$, and the best stability is observed with $l_g \approx 0.5\lambda_g$. Analysis of the data of Fig. 5 leads to the important conclusion that, other conditions being the same, for improvement of the stability of the combustion process it is preferable to select the inner diameter of the injector head channels as large as possible. In application to the LRE combustion chambers with large diameter, it is easier to satisfy the strength requirements and reduce the structural weight. However, higher efficiency of fuel burnup in the combustion chamber is more easily achieved with a smaller channel diameter. Therefore it is necessary to seek a compromise with respect to selection of the gas channel diameter. In the case of assurance of the required stability margin with the aid of selection of the optimal gas channel length $l_g \approx 0.5\lambda_g$, we can vary in a certain degree the other physical parameters of the injector head, specifically the diameter of the channels, to improve the other characteristics of the combustion chamber. Just as in the case of Figs. 2 and 3, in the tests of the injector heads with differing diameter of the gas channels in some regimes of operation there arose tangential oscillations at the first overtone with frequency $\nu = 2.7$ to 3.1 kHz ($l_g = 28$ to 32 mm and 95 to 115 mm).

Figure 6 shows the results of change of the combustible mixture flow velocity at the limit of the oscillatory burning region with $\alpha \approx 1$ as a function of the length of the gas channels of diverging shape with angle at the apex $\varphi = 3$ and 5° (curves 1 and 2), the line 3 shows the dependence of the mixture flow velocity on the channel length for the heads with cylindrical channels of diameter 12 mm, taken from Fig. 2. In all cases of the tests of the heads with diverging channels, the frequency of the oscillations corresponded to the fundamental tone of the tangential oscillations.

We note that with increase of the length of the channels and increase of the expansion angle of the channels of diverging form there arises in the channels the danger of separation of the boundary layer from the channel walls, which leads to change of the combustion fronts. To detect these phenomena we made visual observations of the flame stabilization process (without installing the cylindrical combustion chamber segment) with the objective of determining the limiting angle of conicity and length of the gas channels. The studies showed that for the head with $\varphi = 10°$ and $l_g > 96$ mm separation of the boundary layer took place and the flame fronts penetrated into the channels; for the heads with $\varphi = 3°$ and $l_g = 144$ mm flame stabilization is satisfactory up to the flow velocity $v_g \approx 154$ m/sec, while with $\varphi = 5°$ and $l_g = 132$ mm stabilization is satisfactory up to $v_g \approx 83$ m/sec. Therefore the primary studies were made with diverging channels with conicity angles 3 and 5°.

Figure 7 presents the analogous results of measurements of the combustible mixture flow velocity (at the limit of the oscillatory combustion region with $\alpha \approx 1$) as a function of the length of gas channels of converging shape with $\varphi = 3$, 5, and

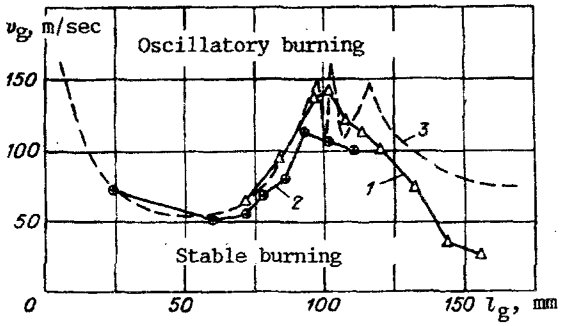

Fig. 6

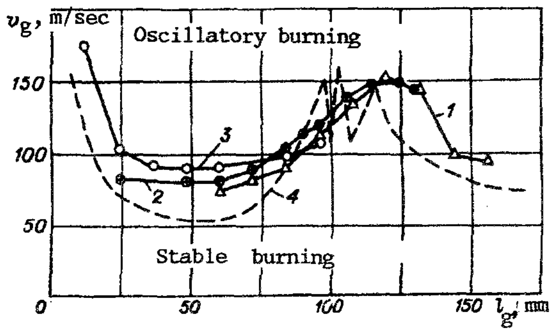

Fig. 7

10°, shown by the lines 1-3; line 4 represents the results of tests for the head with cylindrical channels of diameter 12 mm (see Fig. 2).

Thus, the nature of the relations shown in Figs. 6 and 7 indicates a very significant influence of the length of the gas channels on the limits of stability of the combustion process (based on the flow velocity) for various $\varphi$. Just as for the cylindrical channels, for the conical channels the best and worst combustion process stabilities are obtained for approximately the same channel lengths (respectively for $l_g \approx 0.5\lambda_g$ and $0.25\lambda_g$). There are also some differences: 1) for the diverging channels, deterioration of the stability for long channel lengths ($l_g$ = 108 to 156 mm); 2) for the converging channels, noticeable degradation of the stability for the short channels ($l_g$ = 12 to 84 mm).

This means that the converging channels have some advantage in comparison with the cylindrical channels. Moreover, the converging channels also have the following advantage. As we noted previously, in the experiments conducted with cylindrical channels of different diameter we observed the onset of oscillatory burning at the first overtone of the tangential oscillations for the unfavorable channel lengths ($l_g \approx 0.25\lambda_g$ and $0.75\lambda_g$) for the frequency of the first overtone. Although the oscillations of this frequency were of significantly lower amplitude than the oscillations of the fundamental tone, they were realized for channel lengths close to the optimal length, corresponding to the fundamental tone of the tangential oscillations ($l_g \approx 0.5\lambda_g$). This circumstance forces us to select a length of the cylindrical channels in the injector head that is less than the optimal length. Therefore an important result of the experiments conducted with the conical channels is the fact that with variation of $\varphi$ from 3 to 5° (for both the converging and the diverging channels) oscillatory burning at the frequency of the first overtone of the tangential oscillations was not detected. Consequently, for the conical channels variation of the channel length near the optimal length (to improve the other characteristics of the combustion chamber) is possible in a quite wide range.

Of definite practical interest are the experimental studies of injector heads, in the gas channels of which there are placed additional small tubes of lesser diameter. The additional small tubes were retained at both ends with the aid of plates of thickness 1 mm. Thus, in the gas channels of diameter 23.5 mm there were placed additional small tubes of diameter 18 × 15 mm and 13 × 10 mm. Similarly, in the heads with gas channels of diameter 18.4 mm there were placed additional small tubes of diameter 14 × 12 mm and 10 × 8 mm. In practice such heads could be used with coaxial supply of the propellant components. The results of the experiments showed that the locations of the limits of the oscillatory burning region for the heads with channels of diameter 23.5 and 18.4 mm, in which along the entire length there were placed additional small tubes with outer diameter from 10 to 14 mm, differed very little from one another. For these heads the combustible mixture velocity $v_g$ at the limit of the stability region was respectively from 165 to 185 m/sec. The individual point 5 in Fig. 5 shows the value of the flow velocity at the limit of the oscillatory combustion region for one of the tested heads ($d_g$ = 23.5 mm, diameter of the small tubes 13 × 10 mm). For the heads with the additional small tubes, the mixture flow velocities at the limit were for the heads with channels of diameter 23.5 and 18.4 mm respectively 215 and 180 m/sec. With the installation of small tubes of length 54 mm and diameter 13 × 10 mm at the entrance to the channels of diameter 23.5 mm the stability of the combustion process changed very little in comparison with the heads, in the channels of which the additional small tubes were not installed. Thus, the additional small tubes in the channels have an influence on the stability only when they are installed in the exit section of the channels.

From the examination of the influence of the individual physical parameters of the injector head on the position of the limit of the oscillatory combustion region, we can note that the influence of these parameters is associated with various factors. While the influence of the length of the injector head channels depends on the change of their resonance properties, and the influence of the head permeability is associated with the realization of equality of the velocity of the mixture flow in the gas

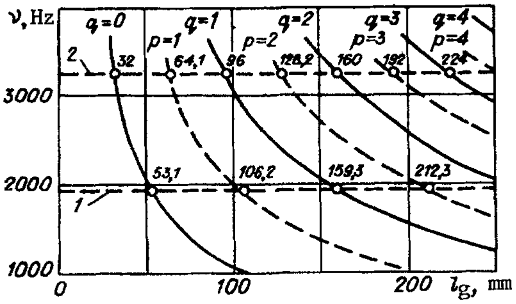

Fig. 8

channels (i.e., nondependence on the permeability), the influence of the diameter of the gas channels and of the additional small tubes of lesser diameter, placed in the mouth of these channels, can presumably be associated with the change of the length of the combustion zone in the chamber.

We shall analyze the primary (obtained in the experiments) result relating to interaction of the longitudinal oscillations of the gas in the cavity of the gas channels and the transverse (tangential) oscillations of the gas in the combustion chamber. Their interaction takes place through the resonance of their natural frequencies. The poorest stability will be provided by the injector heads with gas channels of length $l_g \approx 0.25\lambda_g$, which corresponds to the condition of resonance of the frequencies of the longitudinal modes of the oscillations of the gas channels with the transverse (tangential) oscillations of the combustion chamber, while the best stability will be provided by the injector heads with gas channels of length $l_g \approx 0.5\lambda_g$, which corresponds to "anti-resonance" of these same oscillation frequencies.

It is well known [10] that to the condition of resonance of the frequencies for acoustic systems that are rigidly closed at one end and acoustically open at the other end there corresponds the condition $l_g = (2q + 1)c_g/4\nu$ $(q = 0, 1, 2, 3, \ldots)$, and to the condition of "anti-resonance" of these same frequencies (analogous to acoustic systems that are rigidly closed or acoustically open at both ends) there corresponds the condition $l_g = pc_g/2\nu$ $(p = 1, 2, 3, \ldots)$.

For the specific conditions of conduct of the experiments on the model combustion chamber with a cylindrical segment of diameter 280 mm, Fig. 8 shows the calculated variations of the frequencies of the longitudinal oscillation modes in the cavity of the gas channels of the injector head (denoted by the lines q and p) as a function of the length of these channels; the lines 1 and 2 are the values of the natural frequencies of the tangential oscillations for the fundamental tone and the first overtone. The points of their intersection with the lines p and q denote coincidence of the natural frequencies of the longitudinal oscillations of the gas in the injector head gas channel cavity and the tangential oscillations of the gas in the chamber, the numerals near these points show the values of the channel lengths corresponding to the condition of resonance (solid lines) and "anti-resonance" (dashed lines) of these frequencies. We see from Fig. 8 that to the condition of resonance of the frequencies there correspond, specifically, the injector heads with channels of length 53.1 mm, 159.3 mm, and so on; while to the condition of "anti-resonance" of the frequencies there correspond the heads with channels of length 0 mm, 106.2 mm, 212.3 mm, and so on. These values correspond to the poorest stability of the combustion process with $l_g \approx 0.25\lambda_g$, $0.75\lambda_g$, and so on, and to the best stability with $l_g \approx 0\lambda_g$, $0.5\lambda_g$, $1\lambda_g$, and so on.

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