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RELATIONSHIP BETWEEN THE ACOUSTIC PROPERTIES OF THE BURNER HEAD AND COMBUSTION CHAMBER AND TRANSVERSE VIBRATIONS EXCITED IN A GAS

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As the heat-release rate of the combustion chambers of liquid-propellant rocket engines (LPRE) increases (as their diameter and operating parameters increase), the main condition of design reliability is to provide for stability of the combustion process with respect to the acoustic vibrations of the gas, a high degree of propellant combustion being achieved. Determination of the relationship between the design parameters of the combustion chamber (burner head, cylindrical section, and nozzle) and the stability of the combustion process therein has been the subject of many theoretical and experimental studies [1-4]. In practice, each LPRE combustion chamber underwent a long and exhaustive series of tests to eliminate various types of vibrational processes. The methods of elimination of undesirable effects also dictated the choice of the structural parameters of the combustion chamber. It is well known from experience in the operational development of combustion chambers aimed at ensuring the stability of the combustion process that with increasing diameter of the cylindrical section and length of the chamber, pressure drop at the burner head (for the same pressure in the chamber), and heat-release rate, the stability of the combustion process decreases with respect to both longitudinal and transverse vibrations of the gas. The length of the combustion chamber is usually chosen so that the combustion zone is located entirely in the fire chamber. This imposes significant limitations on the design of the burner head in terms of providing for effective mixing with a sufficient stability margin of the combustion process.

This paper reports on an experimental study of the influence of the diameter and length of the combustion chamber and structural elements of the burner head on the stability of the combustion process with respect to transverse vibrations of the gas, other structural and operating parameters being kept constant.

1. Experimental Objective. The experiments were carried out with cylindrical combustion chambers 196 mm and 280 mm in diameter. A chamber consisted of the following components (Fig. 1); contoured nozzle 1, cylindrical section 2, and burner head 3. The cylindrical section and the nozzle were cooled with water. The burner head consisted of two end plates and of tubes (gas channels) built into them. The thickness of the tube walls was 1 mm. Burner heads of penetrability $\bar{f} = 0.134$ were used in the experiments the term "head penetrability" was taken to mean the ratio of the total area of the gas channels to the cross-sectional area of the chamber). As was shown in [5], the head penetrability in the range $\bar{f} = 0.134$ to $\bar{f} = 0.255$ did not affect the position of the boundaries of the vibrational combustion region. The length of the gas channels in these experiments ranged from 6 mm to 96 mm for the combustion chamber with a cylindrical section diameter of 196 mm and from 6 mm to 204 mm combustion chamber with $D_c = 280$ mm. Tests of the combustion chamber with $D_c = 196$ mm utilized burner heads with only one diameter of the gas channels, $d_g = 12$ mm (36 apertures; honeycombed arrangement of the apertures; spacing between them, 29 mm), whereas experiments with the combustion chamber having $D_c = 280$ mm utilized burner head with different diameters of the gas channels: 12 mm, 18.4 mm, and 23.5 mm (the number of channels in the head varied, while the penetrability was unchanged).

The vibration frequency of the gas in the combustion chamber was recorded with vibrational pressure gauges located on the walls of the combustion chamber. In the experiment involving combustion of a stoichiometric mixture ($\alpha \approx 1$), the frequency of transverse vibrations of the gas for the chamber with $D_c = 196$ mm was 2.7-3.0 kHz, and for $D_c = 280$ mm,

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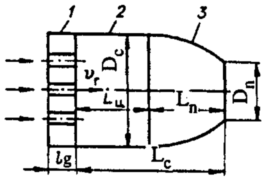

Fig. 1

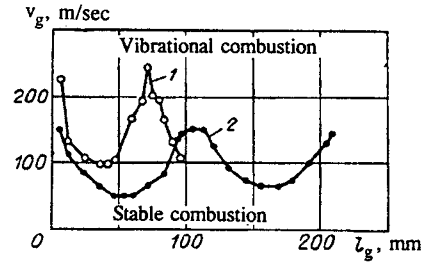

Fig. 2

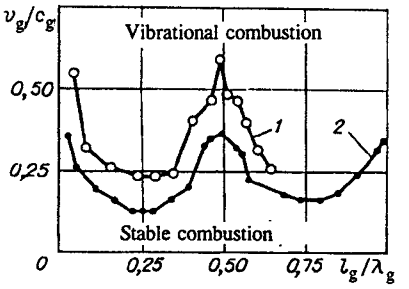

Fig. 3

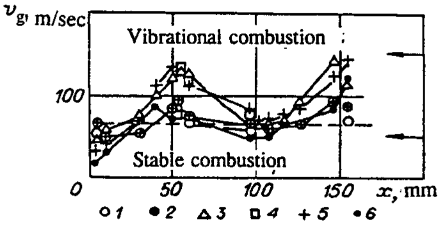

Fig. 4

1.8-2.1 kHz. These frequencies corresponded to the fundamental mode of tangential vibrations of the gas in the combustion chamber. The recorded vibration frequencies of the pressure in the chamber were in good agreement with the calculated frequencies.

In the experiments, the boundaries of the vibrational combustion region were determined in the coordinates, consumption of propellant mixture G vs. excess-air coefficient α. Comparisons of the experimental data were made for $\alpha \approx 1$ (at this value of α, the conditions of heat-release maximality take place during the combustion of the gasoline–air mixture; this causes the most pronounced oscillations of the gas pressure in the combustion chamber as compared to other values of α). A more detailed description of the design of the combustion chamber, burner head and method of conducting the tests is given in [5]. The error in the determination of the location of the boundary of the vibrational combustion region from the consumption of the propellant mixture (i.e., determination of the transition from stable to vibrational combustion) did not exceed 5%, but in the overwhelming majority of the experiments it amounted to 2-3%.

2. Results of Experiments. Figure 2 shows curves of the flow rate of the propellant mixture in the gas channels, at which tangential (fundamental-mode) vibrations of the gas arise in the combustion chamber during the combustion of a stoichiometric mixture ($\alpha \approx 1$), as a function of the length of the gas channels of the burner head with $d_g = 12$ mm for combustion chambers with cylindrical sections 196 mm and 280 mm in diameter with a total chamber length of 360 mm (lines 1 and 2, respectively). It can be seen that the arrangement of heads with different gas-channel lengths results in a significant change in the magnitude of the flow velocity of the propellant mixture at which a transition from stable to vibrational combustion takes place. In the investigated range of variation of the channel lengths for the combustion chamber 196 mm in diameter, there are two distinct stability minima at channel lengths $l_g = 36$-48 mm and 96 mm, and the stability maximum appears clearly at $l_g = 6$ mm and 68-76 mm. The data for $D_c = 280$ mm were taken from [5], which showed that one of the effective ways of improving the stability of the combustion process is to use burner heads with the optimal acoustic length of the gas channels a multiple of 0.5 λ_g, where $\lambda_g = c_g/\nu$ is the length of the sound wave in the medium of the gas channels (c_g being the sound velocity in the channels, and ν, the frequency of the tangential vibrations formed in the combustion chamber). Heads with channels of length $l_g \approx 0.25\ \lambda_g$ and $0.75\ \lambda_g$ provided for the lowest stability of the combustion process. In experiments with a chamber having $D_c = 280$ mm ($t_g = 473$ K, $c_g = 416$ m/sec, $\nu = 1.96$ kHz), $\lambda_g = 212$ mm, and $D_c = 196$ mm ($T = 473$ K, $c_g = 416$ m/sec, $\nu = 2.81$ kHz), $\lambda_g = 148$ mm.

TABLE 1

Notation of Fig. 4	d_r, mm	$\bar{f}$	ζ
1	1	0,807	0,31
2	2	0,62	0,87
3	3	0,46	1,95
4	3,5	0,384	3,34
5	4	0,314	5,67
6	5	0.213	14.70

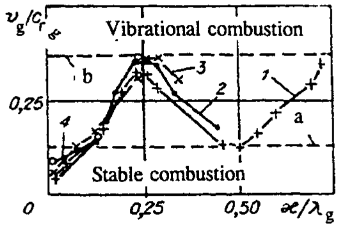

Fig. 5

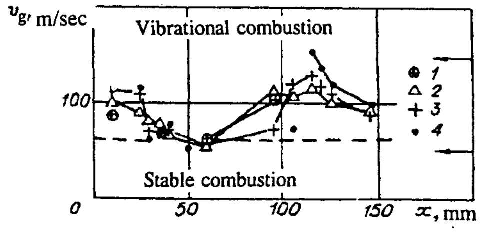

Fig. 6

Figure 3 shows comparative test data (presented in Fig. 2) for combustion chambers with cylindrical-section diameter D_c = 196 mm and 280 mm (lines 1 and 2) in the coordinates, Mach number in burner-head gas channels v_g/c_g (c_g being the sound velocity determined from the gas temperature) vs relative length of gas channels l_g/λ_g.

As is evident from Fig. 3, the highest stability of the combustion process with respect to tangential vibrations of the gas in the combustion chamber is provided by heads with channel lengths $l_g \approx 0.5\lambda_g$ and $1\lambda_g$, and the lowest stability is provided by $l_g \approx 0.25\ \lambda_g$ and $0.75\ \lambda_g$, irrespective of the dependence on the diameter of the cylindrical section of the combustion chamber.

At the present time, two component (emulsion) burner heads in which one of the components of the propellant in liquid form is introduced into another (gaseous) component are used fairly widely in LPRE. As a first approximation, jets of the liquid component of the propellant in emulsion burners may be treated as throttling devices placed inside the gas channels and producing local hydraulic resistances to the flow of the gaseous component. The acoustic properties of such heads differ markedly from those of heads in which there is no introduction of liquid jets. It is well known [6-8] that in acoustic systems with a fixed arrangement of the maxima and minima of vibrational pressure and vibrational velocity along the channels, the placement of any throttling devices around the vibrational velocity antinodes leads to damping of the vibrational processes in these systems. In this connection, it was of interest to model the results of full-scale tests (in order to study the influence of the introduction of liquid jets on the stability of the combustion process with respect to transverse vibrations of the gas in the combustion chamber) with the aid of metal rods placed inside the gas channels at right angles to the flow. Heads with a 12-mm inside diameter of the channels and lengths of 156 mm, 96 mm, 75 mm, and 52 mm were used. The metal rods were welded into the walls of the gas channels in the shape of a cross. Their diameter d_r ranged from 1 mm to 5 mm. The experiments were conducted with a combustion chamber having a cylindrical diameter of 280 mm.

Figure 4 shows the dependence of the flow rate of the propellant mixture in the channels, at which tangential vibrations of the gas arose in the combustion chamber, on the position of metal rods of different diameters along the channels of the head with l_g = 156 mm. Table 1 lists the main structural and design parameters for the heads studied. The hydraulic resistances were calculated from the formula $\zeta = 1.3(1 - \bar{f}) + (1/\bar{f} - 1)^2$, given in [9]. In Table 1, d_r is the rod diameter, f is the degree of openness of the gas channels, and ζ is the hydraulic loss coefficient. In Fig. 4, the arrows indicate the limiting values of the velocity, obtained previously for channels of the same length and diameter (l_g = 156 mm, d_g = 12 mm), but without rods [5]: $l_g \approx 0.5\ \lambda_g$ (upper arrow) and $0.25\ \lambda_g$ (lower arrow). It follows from an examination of the data obtained that when rods 1 mm to 5 mm in diameter were placed at different distances from the mouth of the channels, an appreciable change in the position of the stability boundaries of the combustion process was observed. There were two distinct stability maxima when the rods were located at distances of 50-60 mm ($\varkappa \approx 0.25\ \lambda_g$) and 146-154 mm ($\varkappa \approx 0.75\ \lambda_g$). If, however, the rods were located at a distance of 96-116 mm ($\varkappa \approx 0.5\ \lambda_g$) from the mouth of the channels, the stability was minimal. Note that the

TABLE 2

Notation of Fig. 6	d_0, mm	ΣF_0, mm^2	K, %
1	2	12,56	11,10
2	3	28,25	25,0
3	4	50,2	44,4
4	5	78,5	69,3

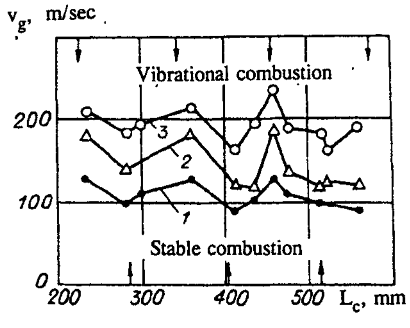

Fig. 7

highest stability (with respect to the maximal flow velocity of the mixture in the channels) was provided by rods 3-4 mm in diameter and approached the maximum possible stability, which is provided by a head with the optimal acoustic length $l_g \approx 0.5\ \lambda_g$ of channels with no throttling devices inside them. When the rods were placed at a distance of 3 mm from the mouth of the channels, the stability decreased steadily as the rods increasingly encumbered the cross sections of the channels. When the rods were located at a distance of $0.25\ \lambda_g$ or $0.75\ \lambda_g$, the stability improved when rods of different diameters were mounted.

Similar curves were obtained for other lengths of the head channels (96 mm, 75 mm, and 52 mm). The maximum flow rate of the propellant mixture at which the combustion was still stable ($v_g \approx 154$ m/sec) was found to be close to the maximum possible rate for the same heads, but without throttling devices [5]. This is illustrated in Fig. 5, which shows the collected data in the form of a dependence of the Mach number in the gas channels of the burner head on the relative magnitude of the location of the rods inside the channels x and on sound wavelength λ_g, and lines 1-4 represent the data for heads with l_g = 156 mm, 96 mm, 75 mm, and 52 mm, and a and b, respectively, give the maximum levels of stability of the combustion process for heads without rods: with nonoptimal length of gas channels $l_g \approx 0.25\ \lambda_g$ and optimal length $l_g \approx 0.5\ \lambda_g$.

Another method of changing the acoustic properties of the burner head (which are conducive to the damping of vibrational processes in gas channels) consists in connecting the cavities of the gas channels of the burner head to the cavity of the closed interchannel space by means of four apertures regularly spaced along a circle in different sections of the channels. Heads with channel lengths of 156 mm and 96 mm (d_g = 12 mm) were used in these experiments.

Figure 6 shows the dependence, analogous to Fig. 4, of the flow rate of the propellant mixture at which tangential vibrations of the gas took place in the combustion chamber during the combustion of a stoichiometric mixture ($\alpha \approx 1$), when instead of setting up rods inside the channels, apertures of different diameters were drilled into the walls of the burner head channels. The space between the burner head flanges into which the gas channels were welded was hermetically sealed; this eliminated the mean flow of the gas from the cavity of the gas channels into the interchannel space or vice versa. Table 2 gives the main structural and design parameters for the studied heads with apertures in the walls (d_0 — diameter of apertures in the walls, ΣF_0 — total area of the four apertures, K — ratio of the area of the apertures to the cross-sectional area of the channels). In Fig. 6, the arrow indicate the limiting values of the flow rate of the propellant mixture at the boundary of the vibrational combustion region for burner heads with the same diameter of the gas channels (d_g = 12 mm) but without apertures $l_g \approx 0.5\ \lambda_g$ (upper arrow) and $0.25\ \lambda_g$ (lower arrow). Thus, it follows from Fig. 6 that with changing diameter and location of the apertures in the walls of channels 156 mm long, as in the case of rods placed in the channels, an appreciable change in the stability of the combustion process was observed. There are two distinct stability maxima when the apertures are located at distances of 10 mm ($l_g/\lambda_g \approx 0$) and 106-116 mm ($l_g \approx 0.5\ \lambda_g$). The lowest stability was provided by heads with an aperture diameter of 5 mm. However, when the apertures were located at distances of 50-60 mm ($l_g \approx 0.25\ \lambda_g$) and 146 mm ($l_g \approx$

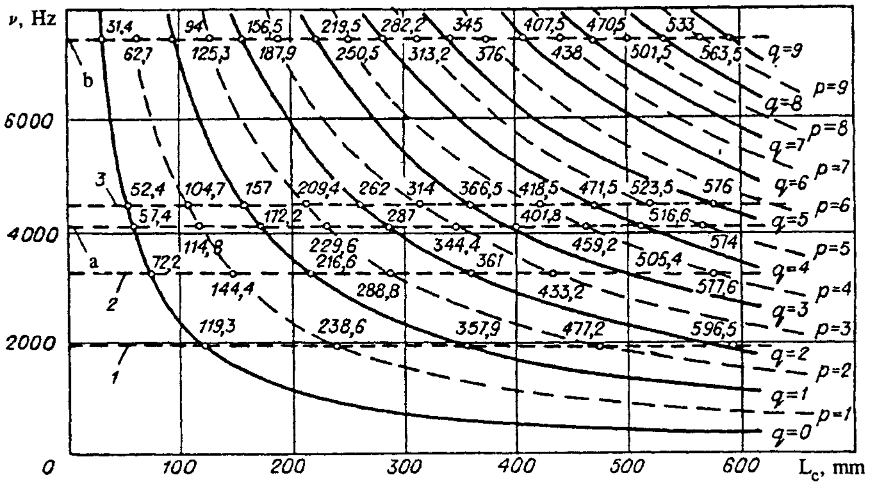

Fig. 8

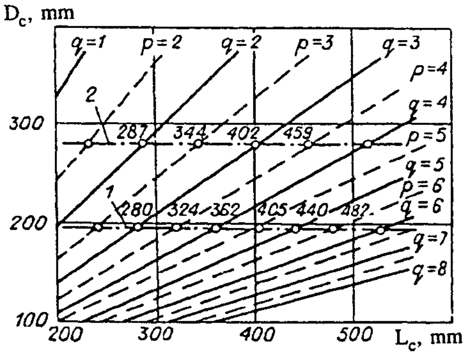

Fig. 9

0.75 λ_g), the stability was lowest and practically independent of the diameter of the apertures in the walls. In experiments with apertures in the walls of gas channels of length l_g = 96 mm, an analogous dependence of the stability of the combustion process on the location of the apertures in the walls of the channels was observed along these channels.

The next series of experiments with a combustion chamber having a cylindrical section of 280 mm involved changing the length of the combustion chamber. In this case, transverse (tangential) vibrations of the gas also took place (these were the vibrations recorded by gauges mounted on the walls of the combustion chamber). By chamber length was meant the total length of the cylindrical section and contoured nozzle. The test results are given in Fig. 7 for heads with gas channels 12 mm, 18.4 mm, and 23.5 mm in diameter (lines 1-3) at their optimal length $l_g \approx 0.5\ \lambda_g$. Analyzing the data of Fig. 7, we note that the stability of the combustion process (characterized as before by the flow rate in the gas channels of the burner head) changed with chamber length. Chambers of length L_c = 235 mm, 360 mm, and 460 mm provided the highest stability for all the diameters of the burner head channels, and chambers of length L_c = 293 mm, 415 mm, and 515 mm gave the lowest stability. The distance between peaks of the highest (or lowest) stability alternated every 100-130 mm (on average, 115 mm). Thus, a periodic alternation of the highest and lowest stability of the combustion process is observed, as was the case with changing length of the burner head channels (see Fig. 2). Such an effect should seemingly be due only to vibrations of longitudinal form in the fire cavity of the combustion chamber. However, in the testing of chambers of different lengths, recording in their fire cavities again showed the presence of transverse (tangential) vibrations, usually of the fundamental mode (ν = 1.8-2.1 kHz).

If the distance of 115 mm is taken as one-half the sound wavelength of certain longitudinal vibrations of the gas in the chamber ($L_c = 0.5\ \lambda_c$), the frequency of these vibrations ($\nu = c_c/\lambda_c$) should be approximately equal to 4.1 kHz (for the conditions of the experiments described, the speed of sound in the combustion chamber, $c_c \approx 940$ m/sec, was calculated for the value $\alpha \approx 1$, i.e., at $T_c \approx 2400$ K). The vibration frequency, equal to 4.1 kHz, is the frequency of the fundamental mode of radial vibrations of the gas for a combustion chamber with D_c = 280 mm.

As a result, the lowest stability of the combustion process will be observed at values $L_c/\lambda_c \approx 0.25\, q$ ($q = 1, 3, 5, \ldots$), and the highest stability, at $0.5\, p$ ($p = 2, 4, 6, \ldots$). Expressing λ_c in terms of the speed of sound in the chamber c_c and of the frequency of transverse (radial) vibrations of the gas ($\nu = \alpha_{mn} c_c/D_c$, α_{mn} being the characteristic number), in the case of coincidence of the frequencies of longitudinal modes and fundamental mode of radial vibrations we obtain

$$L_c/\lambda_g = \alpha_{mn} L_c/D_c.$$

For the fundamental mode of radial vibrations of the gas, $\alpha_{mn} = 1.22$. In this case, the recorded positions of the maxima and minima of vibrational pressure and vibrational velocity will change multiply, $L_c = 0.205 D_c$. Thus, to the lowest stability of the combustion process (see Fig. 7) will correspond combustion chambers of length

$$L_c = 0.205\, D_c q \ (q = 1, 3, 5, \ldots),$$

and to the highest stability

$$L_c = 0.205\, D_c p \ (p = 2, 4, 6, \ldots).$$

The indicated change in the position of the boundary of the vibrational combustion region can be given by the combustion chamber as an acoustic system with a tightly closed end on one side and open on the other. It is well known [8] that the frequency of longitudinal vibrations of the gas for a 1-D system tightly closed acoustically on one side and acoustically open on the other side is expressed as follows: $\nu = (2q + 1)c_c/4L_c$, where $q = 0, 1, 2, 3, \ldots$ For a combustion chamber, the condition of an acoustically tightly closed end is satisfied by the cross section of the fire and plate of the burner head, and the condition of an acoustically open end is satisfied by the outlet section of the combustion chamber nozzle.

Figure 8 shows the calculated dependence of the frequency of longitudinal vibrations of the gas on the length of the combustion chamber for specific experimental conditions during the combustion of a gasoline–air mixture at $\alpha \approx 1$, with the horizontal lines showing the values of the eigenfrequencies of transverse modes: 1-3 – eigenfrequencies of tangential vibrations of the fundamental mode (1.96 kHz), first overtone (3.25 kHz), and second overtone (4.47 kHz), respectively, a – frequency of the fundamental mode of radial vibrations (4.08 kHz), b – frequency of the first overtone of radial vibrations. The points of intersection of the curved lines (longitudinal vibrations) and straight lines (transverse vibrations) correspond to the resonance (continuous lines) of these vibration frequencies. One can readily ascertain that the points of intersection of the curves correspond to the optimal and nonoptimal length of the combustion chamber and "react" only to the fundamental mode of radial vibrations of the gas in the combustion chamber. Indeed, to the resonance condition of the frequencies (points of intersection of continuous lines for longitudinal vibrations and horizontal lines for radial vibrations) correspond combustion chambers with lengths of 287 mm, 402 mm, 517 mm, etc., and to the "antiresonance" condition of these frequencies correspond combustion chambers with lengths of 230 mm, 344 mm, 459 mm, 576 mm, etc.

The periodic variation of the location of the boundary of the vibrational combustion region as the length of the combustion chamber increases cannot be correlated with the combined (longitudinal–transverse) vibrations of the gas.

Figure 9 gives a graphical representation of the curves described above, corresponding to the conditions of resonance q and condition of "antiresonance" p for the frequencies of longitudinal vibration modes with the fundamental mode of radial vibrations, in the coordinates, diameter of cylindrical section D_c vs chamber length L_c, and lines 1 and 2 represent the characteristic lengths of the combustion chambers with cylindrical sections of 196 mm and 280 mm.

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