UNCLASSIFIED

AD 459097

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA

UNCLASSIFIED

ATD Report P-65-9 10 March 1965

Surveys of Soviet-Bloc Scientific and Technical Literature

COMBUSTION INSTABILITY

Analytical Survey

(Report No. 2 in this series)

Aerospace Technology Division
Library of Congress

ATD P-65-9 10 March 1965

Surveys of Soviet-Bloc Scientific and Technical Literature

COMBUSTION INSTABILITY

Analytical Survey

(Report No. 2 in this series)

Aerospace Technology Division
Library of Congress

FOREWORD

This report, prepared in response to ATD Work Assignment No. 53, is the second in a series dealing with Soviet developments in rocket propulsion systems. Based on Soviet open literature available at the Aerospace Technology Division and the Library of Congress, it covers the period from January 1958 to April 1964 and deals with combustion instability in liquid rocket and ramjet engines. The report is divided into two parts; Part I is a survey and discussion, and Part II contains summaries of certain articles used in Part I. Reference numbers of sources summarized in Part II bear an asterisk.

Full translations of some of the source materials used in this report may be available from other agencies or commercially. Interested readers may obtain translation data for individual sources by indicating source numbers from the bibliography list on the form attached at the end of this report and returning it to the Aerospace Technology Division.

TABLE OF CONTENTS

COMBUSTION INSTABILITY

1. COMBUSTION INSTABILITY IN LIQUID ROCKET MOTORS AND RAMJET ENGINES

1. Introduction and Summary

Liquid rocket engines are subject to a wide variety of types of combustion instability. The two basic instability modes are "chugging," a low-frequency instability mode which is caused by interaction between the chamber pressure and the injection flow rate fluctuations, and "screaming," a more harmful high-frequency, acoustic instability mode which may lead to burnout of the motor due to increased heat flux. The causes of screaming are not fully understood, but the sustaining mechanism is apparently nonlinear, i.e., it does not become effective until triggered by a high-amplitude disturbance. An important means of preventing this kind of instability is to prevent any disturbance which may trigger it.

Only two articles [18*, 33*] on low-frequency instability were found in Soviet open literature.

Experimental studies or analyses of high-frequency instability which take into account actual engine operation, i.e., mixing, evaporation, dissocation fuel atomization, etc., were not found in the literature surveyed. However, several theoretical studies by Troshin and Shchelkin [19*], Skobelkin [20*], Artamov [21*], and Zaydel [23*] were found which deal with high-frequency instability under idealized conditions, i.e., with combustion of premixed gas mixtures, and which may be considered to contain important material for stability analysis. Some of the conclusions drawn in these studies may be of practical interest.

The majority of the Soviet studies included in this report deal with the interaction of shock and pressure waves with the flame front. These studies are of high phenomenological interest and are indirectly applicable to combustion stability analysis. In the chapters of his book dealing with instability in rocket and ramjet engines, Raushenbach [22*] leans heavily on Crocco and Cheng's comprehensive stability analysis, but draws some conclusions which may have original value.

2. Low-Frequency Instability

The only theoretical article on low-frequency instability in liquid rocket engines found in the literature surveyed was a study published in 1961 by K. I. Artamov [18*]. In this source, equations for the fuel-feed system and the combustion and evaporation processes were formulated and solved to obtain relationships delineating the regions of stable combustion in terms of dimensionless parameters. Some of the results, including stability diagrams, are presented in the appendix [18*]. The analysis is thorough, following standard mathematical techniques, but seems to indicate that Soviet knowledge concerning important basic problems associated with liquid propellant combustion is less comprehensive than that of Western authors, e.g., Sabersky, Crocco, and Summerfield, who analyzed similar problems during the period 1951 — 1954. This type of instability, which is caused by fuel feed-rate fluctuations, is generally not to be considered particularly harmful. According to Troshin and Shchelkin [19*], such instability can be eliminated by design changes. Raushenbakh [22*], for instance, suggests that under certain conditions a slight shift of the fuel injectors in the axial direction may improve combustion stability.

An experimental study on very low-frequency pulsations (up to 60 cps) in a combustion chamber of a stationary gas turbine was published in 1959 [33*]. In this study temperature, pressure, and flame luminosity pulsations were determined as a function of operating parameters. Low- (1.5—3 cps) and medium-range (10—60 cps) frequency oscillations were found to exist. The low-frequency oscillations were independent of all parameters except the primary air excess coefficient. The frequency of the medium-range oscillations increased with increasing mass flow rate of the air-fuel mixture. These oscillations were attributed to oscillatory combustion. The low-frequency oscillations were found to reach considerable amplitudes, which may be harmful to the turbine.

3. High-Frequency Instability

The majority of the studies included in this section deal with the interaction of shock and pressure waves with the flame front. This subject is closely related to combustion instability, since high-frequency oscillations can be triggered by various perturbations, e.g., by amplified, flame-generated compression or shock waves. Some of the results obtained in these studies have been used by Skobelkin [20*], Troshin and Shchelkin [19*], Raushenbakh [22*], and Zaydel [23*] to derive instability criteria for idealized combustion processes.

In this section of the report, pressure- and shock-wave interaction with flames will be discussed first, and then the sources dealing with stability analyses will be treated individually.

Compression waves occurring in combustion processes have been regarded by Kogarko and Ryzhkov as one of the possible sources of combustion instability in liquid rocket motors [7]. For this reason, apparently, the formation as well as the amplification of compression waves by interaction with the flame front has been studied extensively by leading combustion specialists such as S. M. Kogarko, R. I. Soloukhin, K. I. Shchelkin, and others [5, 6, 7*, 10]. It was found that the flame front is solely responsible for the amplification of compression waves since the fresh gas mixture and the combustion products behave as inert media during passage of the compression wave [5, 8]. The amplification was most pronounced at elevated pressures [5] and reached a maximum at a fuel-rich mixture composition [7*]. Studies with benzene and hexane showed that when the combustion temperature was increased by using oxygen-enriched air instead of air as oxidizer, amplification at an identical fuel-air ratio occurred at a considerably lower pressure [7*]. The lowered combustion stability is evidently caused by the increase in the specific heat release.

The formation and intensification of compression waves in the combustion of methane-oxygen and methane-air mixtures was experimentally studied as a function of mixture composition [6]. The effect of tube length on the amplification of compression waves was also studied in the same source. It was found that the maximum amplitude decreases with decreasing tube length. At a critical tube length, no amplification was observed.

In theoretical studies the interaction between a compression wave and the flame front has been treated either as relaxational frontal interaction [8] or as equilibrium amplification of the refracted wave [9, 10]. In both cases the amplification of the compression wave was considered to be a result of the increase in normal burning velocity. Experimental data obtained in other sources [6, 13*] were also treated on the basis of the assumption that the amplification is caused only by an increase in normal burning velocity, and no allowance for the deformation of the flame front was made. Soloukhin showed later in an experimental study on the intensification of pressure waves that deformation of the flame front is a major factor in wave amplification [14*].

Under certain conditions shock waves can be formed from the flame-generated compression waves ahead of the flame front. These shock waves may be reflected from the chamber walls and cross the flame front several times, which may lead to a loss of combustion stability [16*]. The interaction of shock waves with a flame front is therefore also an important phenomenon related to the assessment of combustion stability. Considerable efforts have been made in this field by leading Soviet scientists.

The interaction of shock waves with the flame front has been studied experimentally by Salamandra and Kogarko [1*, 2, 3, 4] and theoretically by S. M. Kogarko, S. S. Novikov, and K. I. Shchelkin [8, 9, 10, 11, 15].

Salamandra studied experimentally the effect of gas composition and pressure on shock-wave formation [1*, 2, 3]. A mechanism explaining the formation of a shock wave ahead of the flame front was deduced from spark schlieren photographs [16*]. In the same source, it was found that the distance at which the shock is formed ahead of the flame front is a function of the mixture composition, its initial pressure, and the tube diameter and geometry. In rectangular chambers this distance was 2.5 times larger than in cylindrical chemabers [1*]. A simple formula was also obtained for calculating the distance from the ignition point to the point of shock formation in terms of the acoustic velocity and the hydrogen concentration in hydrogen-oxygen mixtures. A detailed mechanism on shock-flame interaction was developed[9], and expressions for calculating the increase in burning velocity due to the passage of a shock through the flame front were derived.

The strongest intensification of shock waves (intensification factor $K = 1.37$, where K is the ratio of the Mach numbers of the shock leaving and entering the flame) was found to occur with stoichiometric hydrogen-oxygen mixtures [16*]. This is in contrast to maximum compression-wave amplification, which occurred in fuel-rich mixtures [7*].

Shock-wave intensification was found constant in the pressure range from 100 to 300 mm Hg; with a further increase in pressure up to 600 mm Hg, it increased linearily [13*]. Increases in the reaction rate and the heat releases were found to be responsible for the intensification of shock waves [13*].

Upon the passage of shock waves through the flame front, considerable increases in the flame surface and the burning velocity were observed [4*].

The formation of shock waves in the combustion of hydrogen-oxygen mixtures has been studied [17*]. It was found that when the head of the combustion chamber is made of heat-insulating material, the formation of shock waves takes place more readily than with metallic chamber heads. This effect is due to the dissipation of energy from the compression waves by heat transfer to the metallic wall. The velocities of shock waves formed in high-speed combustion of hydrogen-oxygen mixtures by reflection from insulated and metallic walls were tabulated [17*]. In the same study interesting results are given concerning the increase in the flame speed of hydrogen-oxygen mixtures through the use of grids. This subject will be discussed in the next report in this series.

Theoretical analyses of the interaction of shock wave and flame front with allowance for relaxation were made by Kogarko and Skobelkin [8, 9, 15]. Skobelkin showed that the relaxation time (10^{-3} —10^{-5} sec), i.e., the time required for redistribution of the heat fluxes after instantaneous temperature and concentration changes caused by passage of the shock wave through the flame front, may be responsible for an increase in oscillations of pressure and other gas parameters and thus lead to instability of rocket motors [15]. The interaction of weak shock waves with the flame front leads to amplification of the passing and reflected waves owing to the increase in the chemical reaction rate during the relaxation period. Skobelkin also derived a formula for calculating the intensification of shock waves [15].

A theoretical analysis of nonrelaxational shock-flame interaction with allowance for the change in burning velocity caused by changes in the thermodynamic parameters in a weak shock wave was made by S. S. Novikov [10]. K. I. Shchelkin developed a mechanism describing the intensification of weak shock waves in a turbulent combustion zone [11].

Oscillatory combustion, i.e., the occurrence of pressure fluctuations in the burning of homogeneous gas mixtures in tubes, has been studied by several Russian authors. S. A. Arbukov, for example, has studied the effect of inert admixtures on oscillatory combustion [24] using a CO-air mixture containing CO_2, N_2, or Ar. He concludes that at the concentration limits at which oscillatory combustion occurs, the heat release rate is constant regardless of the combustible composition. This conclusion was verified by Korobkova [25*], who used CO-air, hydrocarbon gas-air, and propane-air mixtures containing varying amounts of N_2 or CO_2. Both these studies seem to indicate that the heat release rate is the controlling parameter for the occurrence of longitudinal oscillations. This conclusion is in agreement with the finding in source [7*] that amplification of compression waves increases with an increasing heat release rate.

The effect of pressure on oscillatory combustion was studied theoretically by Kurzhunov [27*]. On the basis of the generalized considerations the author concludes that the amplitude of longitudinal oscillations increases with increasing pressure and, at constant pressure, with increasing burning velocity. An increase in tube diameter results in a rapid decrease of amplitude.

A study was made of oscillatory combustion in a combustion chamber fueled with pulverized coal [32*]. Based on Raushenbakh's concepts [22*], a stability diagram in terms of pressure and heat release fluctuation frequencies was derived, and it was shown that in the case studied oscillatory combustion was induced by the circumstance that the phases of the pressure and heat release rate fluctuations coincided. This is attributed to the ignition delay of the coal-air mixture. An experimental study on the effect of pressure, gas composition, and tube diameter on occurrence of oscillatory combustion was made by Kurzhunov [26*]. The experimental results obtained with small tubes (diameter 1 cm) are shown in the appendix [26*]. The most comprehensive treatment of oscillatory combustion was found in Raushenbakh's book [22*]. This author based his treatment of oscillatory combustion on his own theoretical and experimental work, which had been published previously or presented in lectures at the Moscow Physicotechnical Institute. Oscillatory combustion was treated primarily from a generalized theoretical viewpoint. The chapters dealing with combustion instability in liquid rocket engines draw heavily on the work of L. Crocco and S. I. Cheng (Theory of Combustion Instability in Liquid Propellant Rocket Motors), but he writes with authority on the subject, and it appears that some statements are original. Excerpts related to combustion instability are given in the Appendix [22*]. Oscillatory combustion of a confined hydrogen diffusion flame was studied by V. N. Podymov [34*]. The conditions under which oscillatory combustion is induced were determined, and it was found that oscillations occur when the volumetric gas consumption exceeds a critical value. Oscillatory combustion is attributed to interaction between the gas column and the flame.

At a conference on oscillatory and pulsating combustion, several specialists discussed various aspects of oscillatory combustion [35*]. B. V. Raushenbakh expressed the view that oscillatory combustion is sustained by fluctuations not only of the heat release rate but also of the effective burning velocity. D. D. Ryzhov attributed the occurrence of high-frequency oscillations to the interaction between the combustion zone and small pressure disturbances. V. A. Khristich and A. A. Parnas dealt with measuring devices for studying oscillatory combustion. V. I. Skobelkin expressed the opinion that the change in the chemical reaction rate plays a decisive role in the oscillation process.

In summarizing Soviet studies on oscillatory combustion, it may be seen that most of the studies [25*, 26*, 27*] were made with homogeneous gas mixtures in very small tubes and that mostly longitudinal oscillations were considered. For these reasons the results are applicable to rocket combustion only with certain restrictions.

Among the sources which appear to be most relevant for combustion instability is an article published by Skobelkin in 1962 on the theory of relaxational oscillations in combustion chambers [29*]. The author used the mechanism of relaxational interaction between weak perturbations (compression waves) and the flame front developed in other studies [5, 8, 15] to derive a theory for calculating combustion stability criteria and for evaluating the occurrence of pressure oscillations in the gas phase of an idealized liquid combustion chamber. Expressions for the pressure fluctuations, the amplification of standing shock waves, wave absorption, the critical chamber length, and the regions of absolute and relative stability were derived. Some of the formulas are given in the appendix [20*]. Skobelkin drew the following conclusions: Pressure oscillations can be reduced by locating the combustion zone at fundamental or harmonic frequency nodes. Oscillations can be prevented by decreasing the relaxation time (time required for temperature equalization after instantaneous temperature and pressure increase, after passage of the pressure wave through the flame front). This can be achieved by turbulization of the combustion zone or by introduction of metal powder, carbon black or other particles with high thermal conductivity. Design changes may also be used.

Another theoretical study on combustion stability which appears to be applicable to a burner-nozzle combination was published by Artamov and Krutikova in 1962 [21*]. This analysis was made for the cases in which the longitudinal temperature gradient in a duct with a variable area is either variable or constant. For the first case, a graph was obtained of the heat-release-rate parameter μ versus the adiabatic exponent at different inlet Mach numbers. The graph showed that the combustion is stabilized with an increasing Mach number (in the range M = 0.01—0.1) and adiabatic exponent and with a decreasing heat-release parameter. The latter relationship confirms the conclusion in source [7*] that the stability is lowered with an increasing heat-release. The finding that the flow is stabilized with an increasing inlet Mach number and a specific heat ratio is somewhat unusual and is apparently a result of the assumption of variable area flow and other flow conditions which were not fully specified in the article. In the second case, i.e., for a constant longitudinal temperature gradient along the flow duct (distribution of combustion zone over the entire chamber length), it was found that instability does not occur, even at high heat-release parameters. This indicates that combustion stability can be considerably increased by distributing the combustion zone over a wider longitudinal section or, eventually, by using two or more combustion zones. This is in agreement with Raushenbakh's findings [22*].

A very comprehensive treatment of high-frequency oscillations in high-performance combustion chambers is presented by Shchelkin and Troshin [19*]. In this source the instability sources in ramjet and liquid rocket engines are discussed, and combustion instability criteria are derived. The concept that the combustion zone is stable when a weak pressure or shock wave is not amplified by passage through the flame was used. If it is amplified, combustion is unstable. The criterion for occurrence of high-frequency oscillations induced by intensification of weak shock waves shows that combustion may become instable with increasing thermal effect (Q/c_1^2, where Q is the heat of combustion and c_1 is the acoustic velocity in fresh gas), increasing flow velocity fluctuation, increasing turbulence scale, decreasing normal burning velocity, and decreasing chamber length. The occurrence of longitudinal high-frequency oscillations can be prevented by changing one or several of the given parameters. The occurrence of transverse oscillations becomes more probable with an increasing inlet Mach number and an increasing thermal effect. Turbulence parameters, burning velocity, and chamber length have no effect.

No formulas can be derived for the stability of the combustion zone with respect to strong shock waves, and, therefore, numerical solutions were computed for several cases with the gas flow velocity equal to, 50% of, or 10% of the maximum deflagration velocity. The analysis showed, among other things, that the increase in burning velocity caused by passage of the shock is the controlling factor for the occurrence of instability. Stability decreases with increasing thermal effect, increasing specific heat ratio, and increasing fresh-gas velocity.

Finally, in this source [19*] another criterion was derived for combustion instability which is caused by fluctuations of the ignition delay and which is manifested by fluctuations of the ignition front. According to this criterion combustion instability may occur as the activation energy, thermal effect, or inlet Mach number increase and the gas temperature at the inlet to the combustion zone decreases. The same combustion stability criterion as given in [19*] was previously derived in 1959 by analyzing the analogy between the combustion in a detonation wave and in a liquid rocket engine [12]. Formulas for the maximum oscillation frequency, also derived in this source, are considered to be of a qualitative rather than a quantitative nature.

An analysis of combustion stability in liquid rocket engines operating in the so-called induction-controlled regime was made by Zaydel' [23*]. The concept of the induction-controlled operating regime in liquid rocket engines was introduced by Zaydel' and Zel'dovich [28*], who developed a model which takes into account the fact that the fuel is preheated and, therefore, the reaction rate at the injection point is not zero as is usually assumed. The fuel is therefore heated by self-accelerating heating due to the reaction and by heat transfer from the combustion products. Depending on the relation between these two heating processes, which are mainly controlled by the initial fuel temperature and the injection velocity, different operating regimes can be established which are characterized by the distance of the flame front from the injection point. On the basis of this model, the boundaries of the induction-controlled operating regime were derived in terms of dimensionless parameters. Zaydel' [23*] analyzed the induction-controlled regime and derived the inequality $\rho_1/\rho_2 < 3$ (ρ_1 and ρ_2 are the densities of fresh gas and combustion products, respectively) as a criterion for combustion stability with respect to small perturbations. The wavelength of the perturbation was assumed to be small in relation to the chamber dimension and the distance of the flame front from the chamber head. For longwave perturbations different analytical approaches were suggested.

Raushenbakh's book [22*] deals predominantly with the feedback mechanisms underlying oscillatory combustion of premixed mixtures in tubes. The author stresses that instability in liquid rocket engines is caused predominantly by perturbations of the gas mixture formation process. However, he proved that mixture formation is not the only cause of oscillatory combustion. The experiments were conducted with combustion in a tube into which a premixed gasoline-air mixture prepared in a separate vessel was injected under such conditions that interaction between the acoustic oscillations in the tube and the mixture formation process was impossible. Raushenbakh also showed that installation of two longitudinally spaced flow-rectifying grids in the cold-gas zone considerably reduces or eliminates oscillatory combustion caused by large vortexes in the fresh-gas mixture. The distribution of the combustion zone by the use of two or more combustion centers is cited as one of the most effective and universal means for eliminating oscillatory combustion. Damping of acoustic oscillations is also mentioned as being effective. The use of two flame holders located in two different cross-sectional planes to generate two combustion centers is recommended [31*] as an effective means for stabilizing combustion.

4. Conclusions

The analysis of Soviet open sources dealing with combustion instability in liquid rocket or ramjet engines seems to indicate that Soviet theoretical studies on combustion instability are less profound and less comprehensive than comparable Western studies in this field. In view of the apparent achievements in Soviet rocket technology, which are evidently connected with the successful development of high-performance propulsion systems, it may be concluded that theoretical stability analyses were not considered essential for the development of such systems and that, therefore, comprehensive stability analyses were not particularly emphasized. It appears that the Soviet approach to combustion stability problems involved primarily the assessment of the effect of fundamental physicochemical and geometrical parameters on combustion stability and the use of these findings for the semiempirical development of combustion processes with unconventional design and operating features.

From this viewpoint it is of interest to summarize and discuss some of the fundamental causes leading to instability, together with the measures which may be taken to suppress instability. According to the literature sources surveyed, the following factors were found to affect combustion stability:
1) Heat insulation of the combustion chamber head facilities the formation of shock waves in the combustion chamber. Since shock waves may trigger high-frequency instability, insulation of the chamber head may lower combustion stability [17*].
2) A basic factor which is incorporated in several criteria for the occurrence of longitudinal oscillations [19*] is the

parameter Q/c_1^2 (where Q is the heat of combustion and c_1 is the acoustic velocity in the fresh gas). An increase in this parameter which is proportional to entropy leads to combustion instability. To maintain Q/c_1^2 at low values, c_1 has to be increased since a decrease in the heat of combustion cannot be considered practicable because it would lower engine performance. The acoustic velocity (c_1) can be increased only by increasing the temperature of the fresh-gas mixture. This can be achieved by preheating the fuel and/or oxidizer stream before it enters the combustion zone. From a general viewpoint, combustion can therefore be stabilized by preheating the fresh mixture, by distributing the combustion zone over an extended section of the chamber, or by using stepwise combustion with two or more separate combustion zones [21*, 22*]. These combustion zones may be arranged either perpendicular to the chamber axis or parallel to the axis [22*]. Various design variants satisfying the requirement for multiple combustion zones appear to be feasible. For instance, flame holders may be arranged in two cross sections of the chamber [31*]. 3) Stability may be increased when the axial position of the combustion zone is selected so that it is located at the nodes of the fundamental or harmonic frequency of the combustion chamber [20*]. 4) Another important means for increasing the combustion stability is apparently to decrease the relaxation time, i.e., to lower the time interval required for temperature equalization after passage of a perturbation through the flame front. This can be achieved either by turbulization of the combustion zone, or by introduction of metal powder, carbon black particles, or other material with high thermal conductivity [20*]. Since turbulization of the combustion zone may also have a negative effect on stability and lower the blow-off velocities, the most advantageous method for increasing stability appears to be the introduction of metal powder. 5) According to a criterion given in [19*], the combustion stability decreases with decreasing normal burning velocity. Combustion can thus be stabilized by using high normal burning velocities. A high normal burning velocity can be obtained only by selecting a specific type of fuel. For instance, boranes have normal burning velocities several times higher than hydrocarbons. 6) The increase in turbulent burning velocity above the steady-state value which occurs after passage of a weak perturbation or shock through the flame front is considered to be the primary cause of the intensification of perturbations and, therefore, for the occurrence of combustion instability [19*]. The combustion stability becomes more sensitive to an increase in burning velocity as Q/c_1^2 , the specific heat ratio, and the incident flow velocity increase. The sensitivity to an increase in the burning velocity can apparently be lowered only by increasing c_1 (the acoustic velocity of the fresh gas), i.e., by preheating the combustible mixture, as discussed under point 2. 7) According to another criterion [19*] for combustion instability which is connected with the fluctuations of the ignition delay, stability is lowered as the activation energy increases. This instability might be eliminated by introduction of active species, e.g., H, OH, or other ions, generated in a pilot flame or in an initial combustion zone. The introduction of active species was found to substantially decrease the ignition delay times and to increase the combustion stability [29, 30]. Therefore, this type of instability would also be eliminated when several combustion zones were used, as discussed under point 2). 8) Combustion instability induced by vortex formation in the cold gas stream can be eliminated by installation of two longitudinally spaced flow-rectifying grids [22*]. Large vortexes are thus sliced into smaller vortexes which affect the combustion zone much less than large vortexes. Another measure may be to remove sources of vortex formation by structural changes, e.g., by removal of sharp edges, streamlining of contours, etc. No direct measures can be taken to remove instability connected with vortex formation in the combustion zone. 9) Damping of acoustic energy is considered a fundamental way of reducing combustion instability. Damping devices installed in the end section of a combustion tube have been found effective in experiments. Installation of such devices on the wall has not yet been tested and seems to be impractical since it may interfere with cooling of the chamber walls and increase the hydraulic resistance [22*].

In summary, it appears that point 2, 6, and 7 give some indication that Soviet designers may have solved combustion stability problems by designing combustion chambers with two or more combustion zones. For instance, the first combustion zone would be fed separately with a premixed gas mixture and thus be independent of the mixing parameter fluctuations in the main stream. The main combustible stream is thus preheated by passage through the first combustion zone, and combustion in the second or main combustion zone is consequently more stable than without preheating. Several additional combustion zones could be used by introduction of fuel and/or oxidizer downstream from the main combustion zone. Such arrangements, which resemble combustion behind a pilot flame, may also be of great interest from the viewpoint of attaining very high combustion speeds close to those of detonative combustion. [This subject will be discussed in detail in the next report in this series, which will deal with intensification of combustion.]

Two or more combustion zones can also be established by the use of several flame holders, which can be arranged either in two longitudinally spaced cross-sectional planes of the chamber [31*] or in one single plane. The latter arrangement would be more advantageous since the combustion zone would be shorter, but the stabilizing effect would be less pronounced than in the first case.

Concerning the effect of oscillations on the operation of combustion chambers, it is generally believed that oscillations are useful for increasing the combustion efficiency, provided that they are not too intensive and thus harmful to the engine [19*]. From this viewpoint (which is apparently held by many Soviet specialists), it appears possible that attempts were made to control rather than to completely eliminate oscillations.

To summarize this analysis, it may be stated that definite conclusions concerning the Soviet approach to combustion instability cannot be drawn on the basis of the open-source literature available. However, it becomes evident that Soviet researchers have a comprehensive knowledge of phenomena closely related to combustion instability, such as flame-pressure wave interaction, intensification of perturbations by the flame front, formation of shock waves in front of the flame front, flame acceleration, deflagration to detonation transition, and the mechanism of gas detonations. Some of the results obtained in these fields were used to derive criteria for the occurrence of combustion instability. However, no studies on the experimental verification of these criteria were published.

It appears possible that in the design of combustion chambers, attempts have been made to eliminate instability by introducing unconventional design and operating features, such as multiple or distributed combustion zones, the injection of metal powder, placement of flow rectifying grids upstream from the combustion zone, and installation of acoustic energy dampers and designed chamber heads to eliminate the unfavorable effect of heat insulation on combustion stability.

Some factors have opposing effects on stability and general performance characteristics (combustion efficiency, engine weight, etc.). For instance, oscillations improve combustion efficiency but reduce stability, and an increase in the length of the combustion zone improves stability but increases the weight of the chamber. Some factors have a positive effect on both the stability and the performance characteristics: the introduction of metal powder increases the specific heat release and improves stability; the use of grids increases the burning velocity and improves stability. Therefore, a selective combination of design features may be considered to be the basic concept which was used in the design of high-performance combustors. Design characteristics affecting the general performance characteristics, such as flame stabilization with countercurrent jets, the use of flow swirlers for reducing the combustion zone length, and the effect of central and peripheral ignition, will be discussed in the next report in this series.

II. APPENDIX

1*) Salamandra, G. D., and O. A. Tsukhanova. Shock formation in front of the flame front. IN: Fizicheskaya gazodinamika (Physical gasdynamics), Moskva, Izd-vo AN SSSR, 1959. 151-162.

The investigation of shock formation in front of the flame front not only is of theoretical interest but also has great practical significance since the presence of shock in front of the flame front is the necessary condition for the transition from slow combustion to detonation.

Hydrogen-oxygen mixtures were used in the experiments because their combustion process is so rapid that the shock forms relatively close to the head of the combustion chamber.

The process was scanned by frame photography (5,000 to 100,000 frames/sec.)

Detonation chambers of circular and rectangular cross sections were used. The length of the detonation chamber could be varied between 280 and 607 mm. The chamber was closed at both ends by plugs, one with a sparkplug for igniting the mixture. Mixtures containing 25, 33.3, 50, 66.6, or 70% H were used in the experiments.

The following results were obtained:

1. The flame, moving rapidly along the tube, causes perturbations in the fresh gas. A shock wave forms from series of these perturbations which cumulate in one section of the tube or in its extension. This shock wave is clearly visible on photographs.

2. The formation of the shock wave takes place at a given length of the chamber. If the perturbations caused by the flame in fresh gas have no time to form into a shock wave before they reach the end of the chamber, the shock can appear as the result of perturbations deflected from the end of the chamber or from the flame front. The elementary perturbations, as a rule, do not pass through the front of the flame, but deflect from it as from a solid wall.

3. In estimating the process of the shock wave formations in front of the flame, it is possible to use a model of gas motion in front of a piston, which can be treated by Hugoniot equations to determine the distance from the ignition point to the point where the shock is formed. The calculated results were in good agreement with the experiment.

4. The dependence of the distance from the point of ignition to the point of shock formation (X) on the mixture concentration can be described as follows: $X \approx a^2/m^2$, where a is the speed of sound in the mixture and m is the percentage of hydrogen in the mixture.

5. The distance from the ignition point to the point of shock formation depends on the shape of the chamber. In the circular chamber the acceleration of the flame front is much greater than in the rectangular chamber at an equal cross-sectional area. As a result, the value X in the first case is almost 2.5 times smaller than in the second.

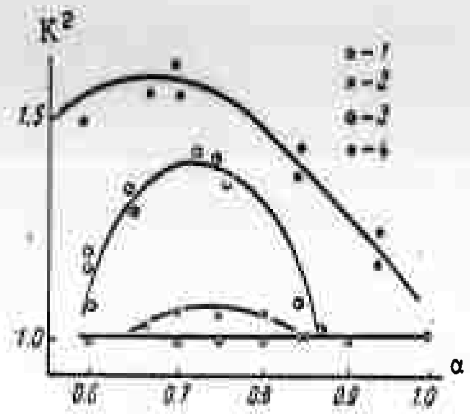
4*) Salamandra, G. D. Interaction of flame with shock wave. IN: Fizicheskaya gazodinamika (Physical gasdynamics). Moskva, Izd-vo, AN SSSR, 1959. 163-166.

This study on flame-shock wave interaction showed that elementary shock discontinuities from which the shock wave is formed and which move towards the flame usually do not pass through the flame front but are reflected from it, causing its deformation.

The shock wave formed, however, readily passes through the flame front and causes the appearance of a cellular flame structure, which considerably increases the burning surface and the burning velocity.

7*) Kogarko, S. M., and D. L. Ryzhkov. Study of the intensification of compression waves in combustion. Zhurnal tekhnicheskoy fiziki, no. 2, 1961, 211-216.

The intensification of compression waves in the combustion of benzene or hexane with nitrogen-oxygen mixtures was studied by piezoelectric recording of pressure waves formed during combustion in a closed vessel at 100—760 mm Hg initial pressure. The intensification of the waves was expressed in terms of the intensification coefficient K^2, which was defined as the ratio of amplitudes of two consecutive waves. Some of the results are shown in Figs. 1-3.



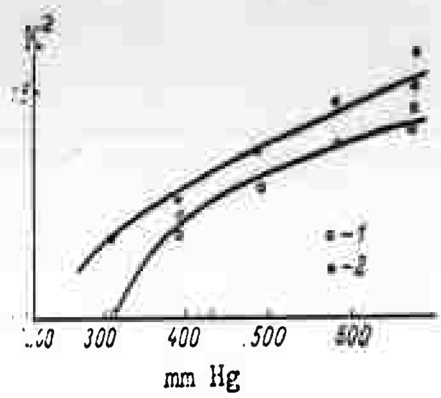


Fig. 1. Dependence of the intensification coefficient K^2 on the mixture composition (air excess factor α) in the combustion of benzene in nitrogen-oxygen mixtures

1 - 21% O_2 + 79% N_2;
2 - 25% O_2 + 75% N_2;
3 - 30% O_2 + 70% N_2;
4 - 45% O_2 + 55% N_2.

Fig. 2. Dependence of the intensification coefficient K^2 on the initial pressure in the combustion of benzene with nitrogen-oxygen mixtures

1 - 40% O_2 + 60% N_2,
2 - 45% O_2 + 55% N_2.

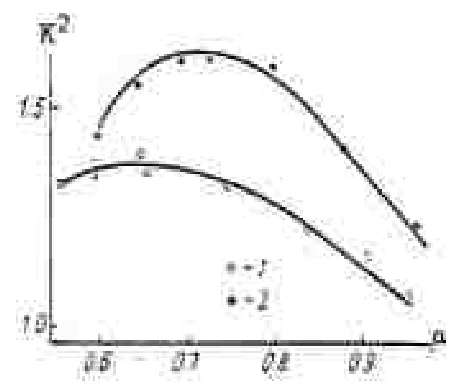


Fig. 3. Dependence of the intensification coefficient on the mixture composition (α) in the combustion of benzene and hexane with nitrogen-oxygen mixtures (40% O_2 +60% N_2) at an initial pressure of 760 mm Hg

1 - Benzene; 2 - hexane.

Fig. 2 shows that in the combustion of benzene in nitrogen-oxygen mixtures, the wave intensification increases monotonically with increasing density of the medium. Fig. 1 shows that the intensification increases with increasing oxygen content in the nitrogen-oxygen mixture. Maximum intensification occurs at a mixture composition of $\alpha = 0.65-0.75$, i.e., in fuel-rich mixtures. It is concluded that when the combustion temperature is increased by decreasing the concentration of the nitrogen diluent at a constant fuel-oxygen ratio, the onset of compression-wave intensification occurs at a lower pressure than with mixtures having a lower combustion temperature (higher nitrogen concentration). For instance, in the combustion with air, no intensification was observed, while at the same fuel-oxygen ratio (α), a substantial intensification occurred with oxygen-enriched air (Fig. 1). Maximum intensification of K^2 (1.84) was observed with fuel-rich mixtures (0.69) at an oxygen concentration of 55%.

13*) Salamandra, G. D., and I. K. Sevast'yanova. Intensification of shock wave during passage through flame front. IN: Fizicheskaya gazodinamika, teploobmen i termodinamika gazov vysokikh temperatur (Physical gasdynamics, heat transfer and thermodynamics of high-temperature gases). Moskva, Izd-vo AN SSSR, 1962. 199-203.

Experiments with H_2-O_2 mixtures containing 40-80% H_2 were conducted in a rectangular shock tube equipped with a window for schlieren photography and with two spark plugs, one located at the tube end and the other at the tube wall. The mixture was first ignited with the plug at the tube end; as the shock front approached, the other plug was ignited by a synchronized mechanism. Thus, a study could be made of the passage of the shock wave through the flame front from the fresh gas into the combustion products and from the combustion products into the fresh mixture. The velocity of the shock wave was evaluated from the differences between the observed shock-wave velocity and the velocities of the fresh gas and the combustion products. A curve of the shock-wave intensification factor K versus % H_2 exhibited a maximum at the stoichiometric ratio. A plot of K versus initial pressure (100—600 mm Hg) shows that K is constant up to 300 mm Hg, and that with a further increase of pressure it increases linearly. It is shown that intensification of the shock wave is not caused by gasdynamic phenomena. During passage of the shock wave through the flame front, the pressure and temperature are increased; as a consequence, the reaction rate and heat release in the combustion zone increase. The changes in the combustion zone cause disturbances which, when moving in the same direction, reach the shock front and cause its intensification.

14*) Soloukhin, R. I. Shock wave refraction on a flame front. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 1963, 40-47.

A study of the interaction of shock wave and flame front has been made to determine the conditions leading to shock-wave intensification and burning-rate increase. In previous Soviet theoretical and experimental studies, the intensification of compression waves by passage through a flame front was associated with either relaxational frontal interaction or equilibrium intensification of the refracted wave. In both cases pressure-wave intensification was explained as resulting from a burning-rate increase caused by the higher temperature of the gas, which is heated by the compression wave. No allowance was made in these studies for deformation of the flame surface. An approximate theoretical evaluation of flame-surface deformation in hydrogen-oxygen flames showed that a shock wave with a pressure difference $\Delta p' = 0.1\ p_1$ (where p_1 is the pressure in the unburned gas) may cause a pronounced deformation by which the flame surface increases several times. The intensification of the shock wave due to flame deformation is considerably stronger than that caused by the increase in the normal burning rate. To study the effect of flame deformation on shock-wave intensification, experiments with hydrogen-oxygen and acetylene-oxygen mixtures were made in a shock tube of 50 x 50 mm cross section. The mixture was spark-ignited at the closed end, and the collision of the incident and reflected shock wave with the laminar flame was scanned by time-resolved schlieren photography and oscillographic pressure recordings. Special experiments were also made with variable ignition delays to study interaction with the collision point located at variable distances from the ignition point. The results showed that the pressure decreased behind the incident shock wave and increased proportionally to the distance from the ignition point behind the reflected wave (after the second passage through the flame front). The overall results of the study demonstrate that flame deformation is the major factor responsible for shock-wave intensification. On the basis of the photographs obtained, a mechanism of the transition from deflagration to detonation is outlined. It is also shown that self-ignition behind the reflected shock wave takes place when $\Delta p/p_1$ is larger than 1.6. This pressure increase corresponds to a gas temperature of 770K, which is close to the ignition temperature of a stoichiometric hydrogen-oxygen mixture (800K). It is emphasized that the detonation wave is formed in the compressed gas between the shock front and the flame, rather than by coalescence of the shock wave with the flame as is usually assumed.

16*) Salamandra, G. D., and I. K. Sevast'yanova. Formation of shock waves ahead of a flame front and their intensification during passage through the flame. Combustion and Flame, no. 2, 1963, 169-174.

The mechanism by which a shock wave is formed ahead of a flame front is described as follows: Expansion of the gas during combustion causes formation of elementary compression waves which propagate before the flame front at a supersonic velocity. Since each following wave propagates in a medium agitated by the preceding wave, the compression waves overtake each other and form the shock wave. This process was deduced from spark schlieren photographs. The distance X from the ignition source at which the shock wave is formed depends on the composition of the combustible mixture, its initial pressure, and the diameter of the tube serving as combustion chamber. The value of X as a function of tube diameter and composition is shown in Fig. 4 and Table 1. It was found that the strongest intensification of shock waves passing through a flame front occurs at a hydrogen content of about 65% (intensification factor, about 1.37).

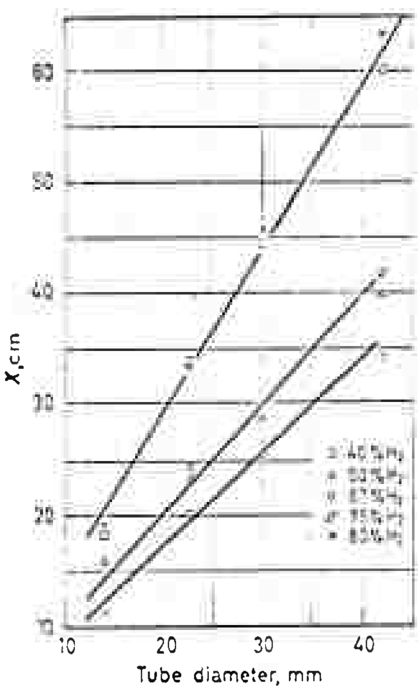


Fig. 4. Dependence of the X value on the diameter of the tube containing the combustible mixture

Table 1. Distance from point of ignition to point of wave development X in hydrogen-oxygen mixtures

% H_2 in mixture	p=400 mm Hg Exptl cm	p=400 mm Hg Calcd cm	p=720 mm Hg Exptl cm	p=720 mm Hg Calcd cm
40	94·2	92	—	—
50	54·5	54·5	39·6	41·5
67	45·5	48·5	34·2	38·5
75	50·4	53	41·6	46
80	72·2	78·5	63·8	67

17*) Kayushin, L. P. Effect of external friction and heat transfer on the motion of the ignition front and shock waves in chemically reactive media. IN: Gazodinamika i fizika goreniya (Gasdynamics and the physics of combustion). Moskva, Izd-vo AN SSSR, 1959. 57-68.

A study of great interest for developing high-intensity combustion processes was made by Kayushin in which he determined the effect of grids and perforated plates on the flame speed of hydrogen-oxygen mixtures. The source describing the experiments was published in 1959. No indication is given of the time when the actual experiments were carried out.

Shchelkin, who studied the effect of tube-wall roughness on the flame speed in detail in 1945-1949, found that the flame speed in tubes with rough walls is several times higher than that in smooth tubes. Since this effect is due to the heat generated by friction, Kayushin assumed that friction generated in a different manner would have a similar effect, and therefore conducted experiments with grids and perforated plates. He used a chamber of 2.3 x 2.6 cm cross section and 17.5 cm length in which the grids or plates were installed 3 and 8 cm from the spark ignition plug. The process was scanned by motion picture and frame photography. The grids were characterized by the parameter $N/\sqrt{\pi r}$, where N is the number of mesh in the grid and r is the mesh radius. Grids with $N/\sqrt{\pi r}$ ranging from 60.5 x 10^3 to 0.04 x 10^3 were used for studying the combustion of hydrogen-oxygen mixtures containing 33, 50, 67, and 82% H_2. The diaphragms were made of brass plates 0.5 mm thick with orifices 0.01, 0.4, 0.8, or 1.6 cm in diameter.

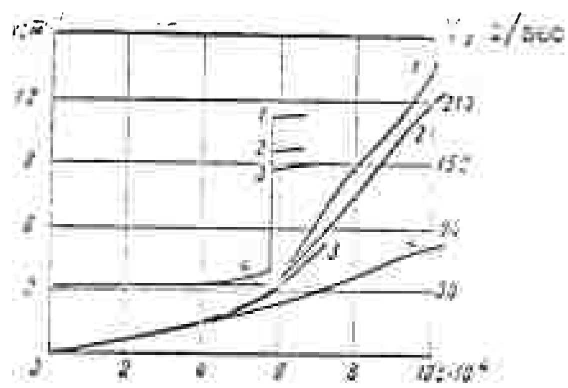


Fig. 5. Time dependence of the path travelled by the flame front in a mixture of $H_2 + 2O_2$ for three different grids

1, 2, 3 - Grids with successively decreasing values of $N/\sqrt{\pi r}$; 4 - combustion without grid.

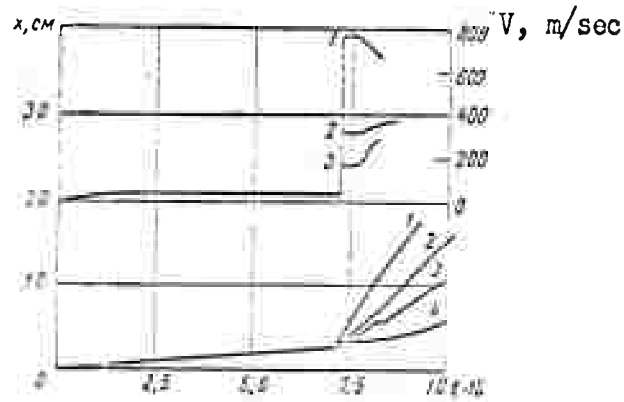


Fig. 6. Time dependence of path travelled by the flame front in hydrogen-oxygen mixtures in a chamber with a diaphragm

1, 2, 3 - Orifice diameters successively increasing; 4 - combustion without diaphragm.

Figs. 5 and 6 show the path of the flame front velocities obtained after passage through the orifices. It can be seen from the figures that with $H_2 + 2O_2$ mixtures and mixtures containing 82% H_2, the flame speed increased considerably after passage through the grids or diaphragms. The effect of the diaphragms was more pronounced than that of grids, and combustion was of detonative character. With stoichiometric mixtures ($2H_2 + O_2$), detonations having a velocity of 5500 m/sec occurred with both grids and diaphragms, regardless of the orifice diameters. The detonation velocity after the grid was much higher than that of a normal detonation and decreased to about half its velocity at the chamber outlet.

With almost stoichiometric mixtures (50% and 67% H_2 concentration), the relationship between the velocity and the orifice diameter could not be determined, since detonation occurred with all orifice diameters. Strong compression waves were observed in front of the flame front with both grids and diaphragms.

Based on Prevoditelev's formula the following relationship was derived for the flame speed in the presence of a grid:

$$w_T = g_1 + \lambda \frac{2\eta_0}{\rho(T_1 - T_0)} \cdot \frac{N}{r},$$

where g_1 is the normal burning velocity, T_0 is the initial gas temperature, T_1 is the ignition temperature, ρ is the gas density, λ is a parameter depending on the gas velocity and temperature distribution, η is the viscosity, r is the diameter of the mesh, and N is the number of the mesh.

According to the formula the velocity would increase without bonds with increasing N/r. However, experiments showed that with a grid of $N/\sqrt{\pi r} = 66.5 \cdot 10^3$ (fine mesh) the velocity decreases, owing to heat transfer from the flame to the grid. Therefore the mesh of the grid has to be selected so as to ensure a minimum heat transfer from the flame to the grid.

The interaction between the compression waves formed during fast combustion and the chamber walls was also investigated in this study. It was found that when the wall of the chamber head is made of heat-insulating material, the formation of shock waves takes place more readily than with metallic walls. This is due to the energy dissipation from the compression waves caused by heat losses to the metallic walls.

Table 2. Shock wave velocities (measured with an accuracy of 50 m/sec)

Conc. H_2, %	V_1, m/sec	V_2, m/sec	$V_2 - V_1$, m/sec
33,3	0	1080	1080
50	1190	1300	110
66	1400	2045	645
67	1350	1820	470
68,6	1595	2200	605
79	1640	2175	535
84	0	2420	2420

V_1 is the velocity of a shock wave formed in a chamber with metallic wall. V_2 is the velocity of a shock wave formed in a chamber with insulated wall.

Table 2 gives the velocities of shock waves formed in fast combustion of hydrogen-oxygen mixtures by reflection from insulated and metallic walls.

Thus, by insulating the wall of the chamber head, it is possible to obtain shock waves also in short chambers or with mixtures which with metallic walls do not form shock waves.

The following are the principal conclusions of the study:

Grids perpendicular to the axis of a combustion-chamber considerably intensify the combustion process. With grids the flame speed is 5—8 times higher than without grids. The flame speed of mixtures with compositions far from stoichiometric increases linearly with an increasing ratio of mesh number to mesh radius. This ratio characterizes the hydrodynamic flow resistance of the grid. With stoichiometric mixtures after the grid, overcompressed detonation waves are formed (5500 m/sec) which decrease their velocity to the normal detonation speed at the chamber outlet.

18*) Artamov, K. I. Stability of liquid-fuel rocket motor operation. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Mekhanika i mashinostroyeniye, no. 1, 1961, 64-69.

An analysis was made of low-frequency liquid rocket motor instability caused by interaction of the fuel injection rate and the chamber pressure. Equations for the evaporation of the fuel, mass balance in the combustion chamber, and the fuel injection process were derived to obtain characteristic system equations. Stable operation was considered as a function of the following four dimensionless parameters:

$$\tau_p = \frac{t_p l}{a}; \ \tau_k = \frac{t_k l}{a}; \ h_\varphi = \frac{\Delta p \varphi}{pko}; \ h_B = \frac{\rho r_0 a}{pko},$$

where τ_p is the ratio of the time lag to the time required for a sound wave to travel through the feed line (l/a), τ_k is the ratio of the residence time of the gas in the chamber (divided by adiabatic exponent γ) to l/a; h_φ is the ratio of the pressure drop in the injection nozzle to the chamber pressure; and h_B is the ratio of the stagnation pressure of the liquid to the chamber pressure (t_p is the evaporation time, t_k is the residence time of the gas divided by γ, a is the acoustic velocity, and l is the length of the fuel feed line). The results are plotted in Fig. 7.

The stable region located on the right side of the diagram is delineated by the smooth curve in the upper part and the broken curves on the left side. When the pressure in the fuel tanks is lowered (during thrust reduction of the motor), the operating point shifts to the left side and upwards. Therefore, stable and

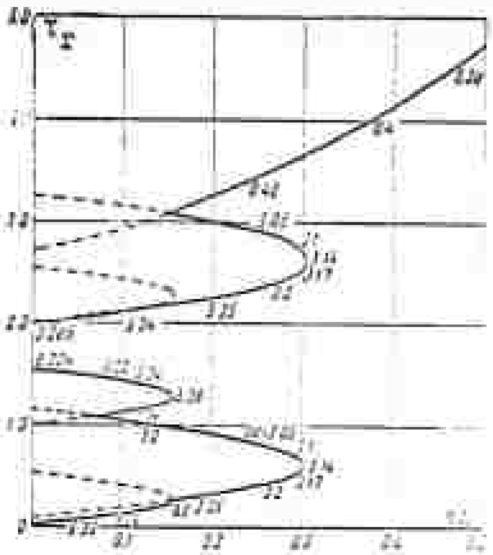


Fig. 7. Stability boundaries in the plane h_ϕ, τ_p at $h_B = 2$, $\tau_k = 1$, and $k = 1, 2$ and $n = 1, 2$ ($n = 1$ corresponds to the fundamental tone $n = 2, 3$ to the higher harmonics; $k = 2k\pi$)

instable regimes may alternate during thrust reduction. An increase in τ_p does not make the motor operation stable when the operating point (τ_p, h_φ) is located above the smooth curve in the upper part of the diagram.

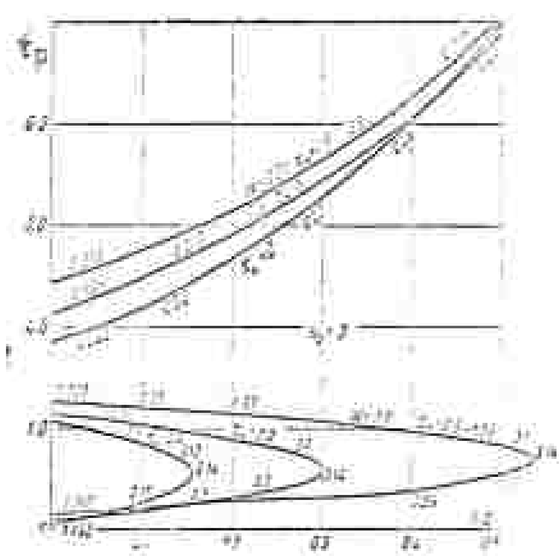


Fig. 8. Same as Fig. 7, but only for the upper limiting curve and the broken curve for $k = 0$ and $n = 1$ ($a = \omega l/a$; ω = frequency)

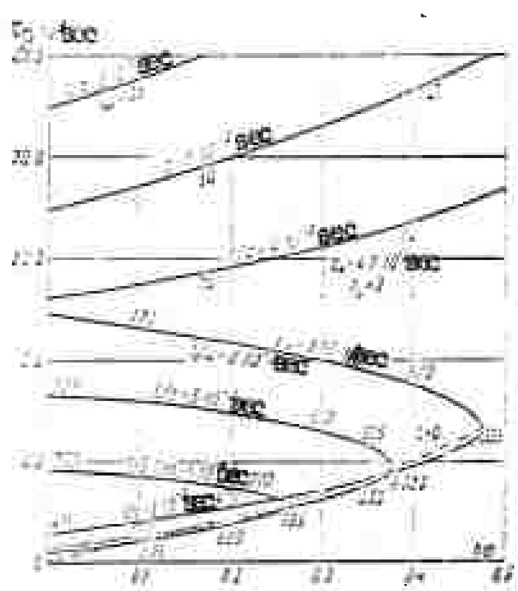
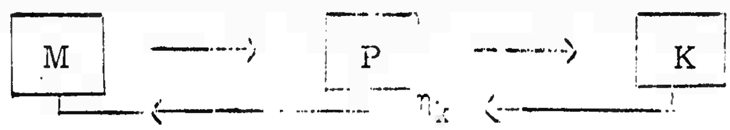


Fig. 9. Stability diagram for various l/a

Fig. 9 shows that an increase in the length of the fuel feed lines affects stability in two ways: it narrows ths stability range, owing to an increase in the surface of the serrated curve, but it widens the range due to a shift of the upper limiting curve.

The operation of a liquid fuel rocket motor can be represented schematically as follows:



where M represents the injection process, P is the evaporation process, and K is the combustion process. The characteristic equation of such a system, is K(q), M(q). P(q) = 1 (q = differential operator). M(q), P(q), and K(q) are transfer functions which must be known for stability analysis. They can be expressed in terms of h_{φ}, h_B, etc. For complex fuel injection systems it is advisable to determine the individual transfer functions by experiments.

19*) Shchelkin, K. I., and Ya. Troshin. High-frequency oscillations in forced combustion chambers. IN: Gazodinamika goreniya (Gasdynamics of combustion). Moskva, Izd-vo AN SSSR, 1963. 215-238.

Oscillations in ramjet combustors may be caused by three types of mechanisms: 1) Aerodynamic instability, which may result from turbulence, vortex separation from the flame holder, or flow separation from the diffusor wall. These oscillations are not harmful unless they are intensified by interaction with the combustion zone. 2) Oscillations may be caused by fluctuation of the fuel feed rate, which leads to heat release fluctuations. This instability can be removed by design changes of the fuel system. 3) The most harmful oscillations are caused by the interaction of longitudinal, transverse, and radial acoustic or weak shock waves with the turbulent combustion zone. The most promising means of suppressing this type of oscillation is by damping of the acoustic or weak shock waves generated by the combustion zone. Another possible means of preventing these oscillations is to weaken the feedback interaction mechanism between the waves and the combustion zone. This possibility is rather limited, since with increasing performance parameters of the combustion chamber (heat release, combustion gas velocity), the tendency towards shock-wave intensification increases. However, some possibilities of weakening the feed-back interaction do exist, and the studies on the interaction between shock waves and the combustion zone are thus not only of theoretical but also of practical interest.

With the exception of some aerodynamic instability modes of ramjet combustors, the instabilities in rocket combustors are caused by basically similar mechanisms. However, in the case of liquid rocket engines another instability source exists which is caused by the internal instability of the flame front which is similar to the instability of a detonation wave front. This instability is due to the consecutive ignition of the premixed and heated combustible mixture.

Concerning the effect of oscillations on combustor operation, it is generally believed that oscillations may be useful for increasing the combustion efficiency, provided that they are not so intensive as to harm the engine.

An analysis of the intensification of weak shock waves in a turbulent combustion zone yielded the following expression for the intensity of the weak shock wave as a function of burning velocity:

$$\Delta p = c_1 \frac{q \cdot M_1}{c_1 + c_3} \cdot \Delta u_+ ,$$

where Δp is the pressure drop across the shock wave; c_1 and c_3 are the acoustic velocity in the fresh gas and combustion products, respectively; M_1 is the Mach number of the fresh gas flow; q is the ratio of heat release to initial internal energy of the gas; Δu_+ is the increase of burning velocity above the steady-state value

$$\left(\Delta u_+ = \frac{u' - u_+}{u_+}\right),$$

where u'_+ is the non-steady-state flame speed relative to the fresh gas velocity, and u_+ is the steady-state flame speed relative to the fresh gas velocity.

The equation shows that the shock wave is generated by an increase in the burning velocity. If this increase is absent ($\Delta u = 0$), Δp will be 0 and no shock wave is formed.

The reverse problem, i.e., the effect of a weak shock wave on the burning velocity, was also analyzed in detail and the following expression was derived for the increase in the turbulent burning velocity caused by a weak shock wave:

$$\Delta u_+ \sim \frac{c_1}{c_1 + c_3} \frac{wg}{u_1} = \frac{1}{c_1 + c_3} \frac{wg}{M_1},$$

where u_1 is the fresh gas velocity relative to a stationary flame front; c_1 and c_3 are the acoustic velocities in the fresh gas and the combustion products, respectively; w_g is the gas velocity behind the shock front relative to the gas velocity before the front; and M_1 is the Mach number of the fresh gas flow. The analysis also showed that the increase in turbulent burning velocity caused by passage of the shock wave is proportional to the turbulence generated by the shock wave.

The following criterion was derived for the occurrence of longitudinal high-frequency oscillations caused by intensification of a weak shock wave in a turbulent combustion zone:

$$B \frac{c_3 c_1}{(c_1 + c_3)^2} (\gamma - 1) \frac{Q}{c_1^2} \left(\frac{v'}{u_n}\right)^m \frac{l}{L_k} \geqslant 1,$$

where B is a constant close to unity, γ is the specific heat ratio, Q is the heat of combustion, v' is the velocity fluctuation, u_n is the normal burning velocity, L_k is the combustion chamber length, l is the turbulence scale, and m is an exponent ranging from 0.5 to 1.

This formula shows which measures can be taken to suppress the occurrence of longitudinal, high-frequency oscillations in liquid rocket engines. For actual conditions in a combustor, corrections have to be introduced for individual cases. For the occurrence of transverse oscillations, the following criterion for the instability of a combustion zone to weak shock waves was obtained:

$$(\gamma - 1) \frac{c_1 c_3}{(c_1 + c_3)^2} \frac{Q}{c_1^2} M_1 \geqslant 1$$

(notation as in previous formulas).

Numerical evaluation of both criteria for longitudinal and transverse oscillations showed that the turbulent combustion zone has a relatively high stability to weak shock waves. The criteria become larger than unity (loss of stability) only at high heat release rates, which are not encountered in air mixtures. In reality, however, instability in air mixtures is experienced. This contradiction is attributed to simplifications made in the derivation of the criteria. Therefore the criteria can be considered only as approximations. In practice, the term on the left side of the inequalities may be only permitted to reach a value smaller than unity before instability occurs.

Similar criteria for the instability of a combustion zone to strong shock waves cannot be derived, and therefore numerical calculations with an M-20 computer were made on the basis of the generalized Hugoniot equation for the following cases: 1) The velocity of the initial gas mixture equals the critical velocity, i.e., the maximum deflagration velocity $M_1 = (M_1)_{cr}$ (the cross section of the nozzle equals that of the combustion chamber). 2) The velocity of the fresh gas is one-half the maximum deflagration velocity, $M_1 = 0.5(M_1)_{cr}$. 3) $M_1 = 0.1(M_1)_{cr}$. For each regime, thermal effects (Q/c_1^2) of 10, 30, and 70 were assumed. A total of 18 variants were computed. Some of the results are shown in Figs. 10—15.

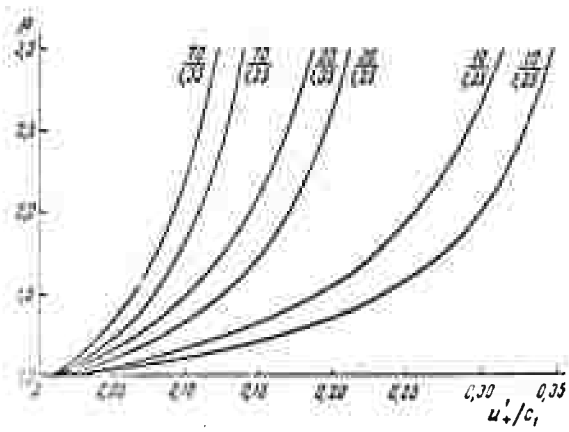


Fig. 10. Dependence of the intensity of a shock wave propagating toward the chamber head in a rocket combustor on the ratio of the flame speed to the acoustic velocity in a fresh gas mixture $(u_+^{\prime}/c_1)$ $(\mu = p_2/p_1$, shock wave pressure ratio). The calculations were made for different Q/c_1^2 (Q = heat of combustion) by the use of a generalized Hugoniot equation for equivalent nozzle convergence; the initial gas velocity (M_1) was taken as 0.1 of the maximum deflagration velocity $(M_1 = 0.1\ (M_1)_{cr})$.

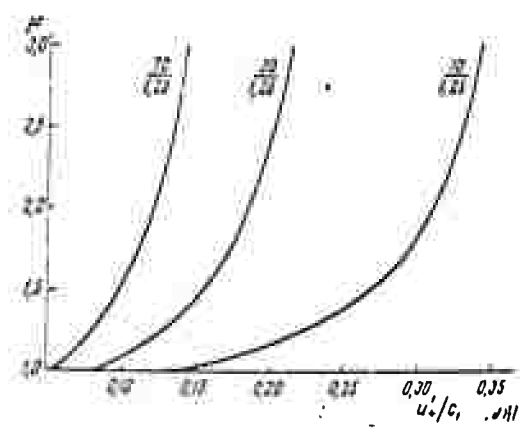


Fig. 11. Same as Fig. 10, except that $\gamma = 1.25$ and the nozzle convergence corresponds to a more forced combustion regime at $M_1 = 0.5\ (M_1)_{cr}$

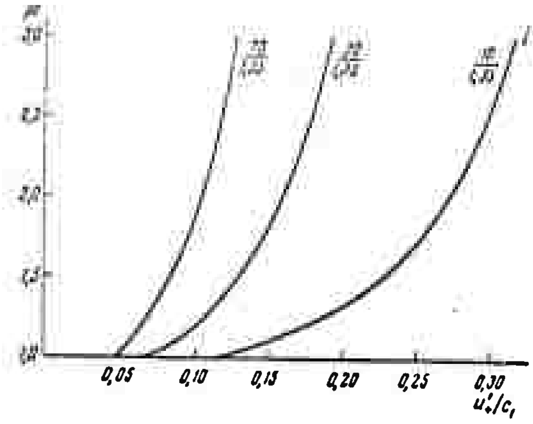


Fig. 12. Same as Fig. 11, except that $\gamma = 1.35$

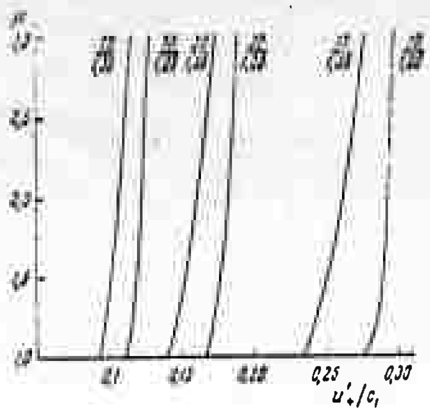


Fig. 13. Same as Fig. 10, but for a nozzle without convergence, i.e., for a maximum deflagration regime, $M_1 = (M_1)_{cr}$

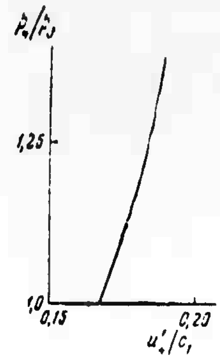


Fig. 14. Dependence of the pressure drop across the shock wave propagating in the products of a steady state deflagration on the dimensionless burning velocity (u'_+/c_1). Calculation by accurate formulas by use of a generalized Hugoniot equation ($\mu = 3$, $\gamma = 1.25$, $Q/c_1^2 = 30$).

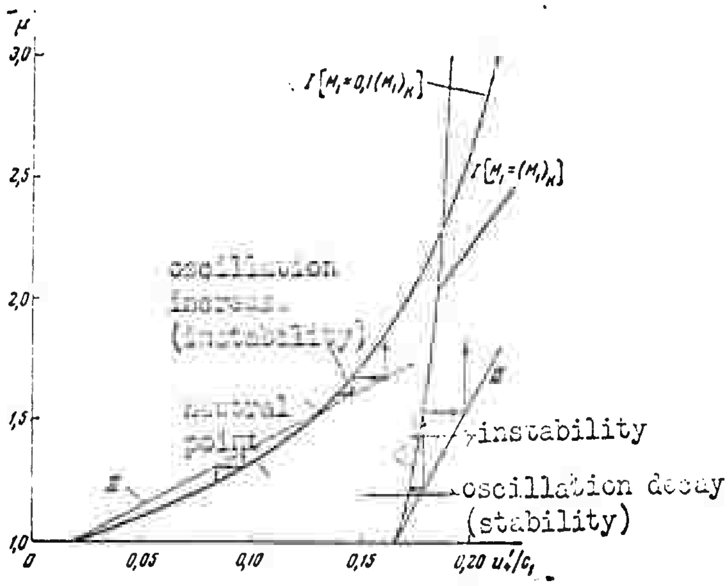


Fig. 15. Dependence of the pressure drop across the shock wave propagating in the fresh gas on the dimensionless burning velocity ($\mu = f(u'_+/c_1)$ - wave I). These curves were obtained by exact formulas and by use of the generalized Hugoniot equation. Lines II represent the dependence of the dimensionless burning velocity on the pressure drop across the shock wave ($u'/c_1 = f(\mu)$. The lines were obtained by analysis of the interaction of weak shock waves with the turbulent combustion zone. $Q/c_1^2 = 30$; $\gamma = 2.25$, at $M_1 = 0.1\ (M_1)_{cr}$ and $M_1 = (M_1)_{cr}$.

Figs. 10—13 show that the increase in burning velocity required to give a certain pressure ratio (p_2/p_1) in the shock wave decreases with increasing thermal effect (Q/c_1^2), with increasing specific heat ratio (γ), and with increasing velocity of the fresh gas (M_1). Under all conditions the increase in the burning velocity has a pronounced effect on the generation of pressure fluctuations. The combustion regime becomes more sensitive to changes in burning velocity as γ, Q/c_1^2, and M_1 increase.

Fig. 15 shows that the exact calculation of the shock wave intensity corresponding to an increase in burning velocity in rocket engines can be used for determining the regions of attenuating, neutral, and intensifying oscillations. In Fig. 15 the calculated dependence between the flame speed and the shock wave intensity is represented by the straight lines II. At low fresh gas velocity, $M_1 = 0.1\ (M_1)_{cr}$, the curve I representing the relationship between the shock-wave pressure ratio and the burning velocity intersects curve II. The region of attenuating shock waves is bounded by the neutral point and curve II. The entire region below the intersection point is stable. In this region arbitrary perturbations such as caused by vortex separation from the diffusor or the flame holder are not intensified in the combustion zone and remain constant. If on the other hand the source of perturbation generates shock waves which exceed the intensity given by the pressure ratio corresponding to the neutral point, the shock wave is intensified in the combustion zone and instability occurs. With increasing flow velocity of the fresh gas, $M_1 = (M_1)_{cr}$, the possibility of attenuation of the shock waves decreases as shown in Fig. 15.

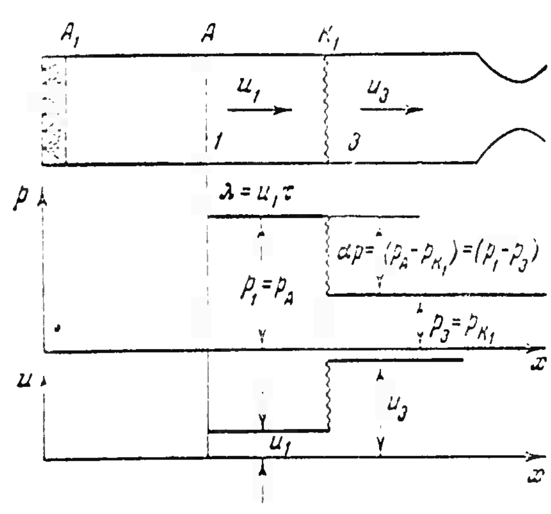


Fig. 16. Diagram of rocket combustion chamber

A new criterion for the instability of the combustion zone caused by gradual ignition of fuel was derived on the basis of the simplified scheme of a rocket combustion chamber shown in Fig. 16.

Evaporation, mixing, and heating of the fuel takes place in the zone A_1-A. In plane A, self-ignition of the fuel starts; combustion is completed in plane K_1. By analogy with a detonation wave, plane A is considered to contain fresh gas in the initial state; the combustion products in plane K_1 will thus be located on a weak deflagration branch of the Hugoniot adiabate (see Fig. 17).

From this thermodynamic analogy, the following criterion for the instability of the combustion zone, manifested by fluctuations of the ignition front (due to ignition delay fluctuations), was derived:

$$(\gamma - 1)^2 \frac{E}{RT_1} \cdot \frac{Q}{c_1^2} M_1^2 > 1,$$

where T_1 is the gas temperature in plane A (other notations are identical with those used in the previous formulas).

Formulas for the maximum oscillation frequency were also derived and, as an example, a maximum frequency of 6400 cycles was calculated for a combustion chamber (1 m long) operated with gasoline at a fresh-gas velocity of 50 m/sec and an induction period of 2.5×10^{-3} sec. Formulas derived on the basis of the analogy of the process in a combustion chamber with a detonation wave may be considered to be of a qualitative rather than a quantitative nature.

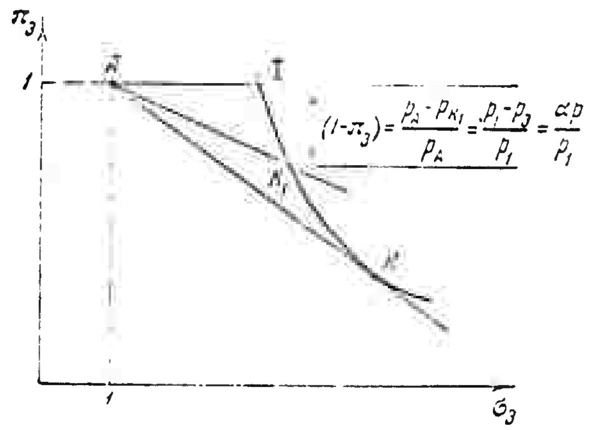


Fig. 17. Deflagration branch of Hugoniot adiabate

20*) Skobelkin, V. I. Theory of relaxational oscillations in a combustion chamber. Zhurnal tekhnicheskoy fiziki, no. 3, 1962, 346-355.

The mechanism proposed previously [5, 8, 15] for relaxation interaction between weak perturbations (compression waves) and the flame front was used by V. I. Skobelkin to develop a theory for calculating combustion stability criteria and for evaluating the occurrence of pressure oscillations in the gas phase of a liquid rocket combustor. Expressions were derived for the pressure fluctuations, the amplification of standing waves, wave absorption, the critical chamber length, and the regions of absolute and relative combustion stability. The following expression was obtained for the pressure fluctuations:

$$P_i' = C_i^* e^{kt} \left\{ e^{\frac{kx}{a_i}} \cos \omega_0 \left(\frac{x_i}{a_i} + t + \alpha_i \right) + (-1)^{\nu_i} e^{-\frac{kx_i}{a_i}} \cos \omega_0 \left(-\frac{x_i}{a_i} + t + \alpha_i \right) \right\},$$

where c_i^* and α_i are arbitrary values of the amplitude and phase at an initial moment of time.

The amplitudes at the cold chamber wall vary according to the relationship:

$$A_n(t) = 2C_{n1} e^{k_n t},$$

where k_n is calculated by the formula:

$$k = \varkappa_1 \mu \frac{\left\{ \frac{1}{\varkappa_2} \left[m + (\varkappa_2 - 1) \frac{\mathcal{E}}{RT_2} \right] z - \frac{\varkappa_1 - \frac{T_1}{T_2}\varkappa_2}{\varkappa_1 (\varkappa_2 - 1)} \frac{T_2}{T_1} \frac{P}{h_m w} \lambda \right\} \frac{\omega_0^2}{\varkappa_2 - 1} - \frac{\lambda}{\varkappa_2^2} \left[\left(\varkappa_1 - \frac{T_1}{T_2} \right) \frac{\mathcal{E}}{RT_2} + \frac{T_1}{T_2} m \right] \frac{a_2^2 h_m w}{a_1^2 P} \left(\frac{\mathcal{E}}{RT_2} - m \right)}{\left(\frac{h_m w}{\varkappa_2 P} \right)^2 \left(\frac{\mathcal{E}}{RT_2} - m \right)^2 + \frac{\omega_0^2}{(\varkappa_2 - 1)^2}}.$$

With allowance for energy dissipation due to the chemical reaction, heat conduction, and viscosity, the following expression was obtained for the pressure fluctuations:

$$P_i' = e^{-\gamma_{in} t} C_{1n}^* e^{(k_n - \gamma_{in} a_i) t} \left\{ e^{\frac{k_n x_i}{a_i}} \cos \omega_n \left(\frac{x_i}{a_i} + t + \alpha_{in} \right) + (-1)^{\nu_i} e^{-\frac{k_n x_i}{a_i}} \cos \omega_n \left(-\frac{x_i}{a_i} + t + \alpha_{in} \right) \right\},$$

where k_n is determined by the same formula as given above and from $b_n = \gamma_{1n} \cdot a_1 = \gamma_{2n} \cdot a_2$.

When $k_n - b_n > 0$, the amplitude increases with time; when $k_n - b_n < 0$, the oscillations decay. As an example, the critical length was calculated as 10 cm for the combustion of methane in air in a tube 2 cm in diameter. This result is considered in fair agreement with theory.

The following conclusions were drawn from the results: Pressure oscillations can be reduced by locating the combustion zone at the nodal points of the fundamental frequency or at the nodal points of a group of first harmonics. The occurrence of oscillations can be prevented by substantially decreasing the relaxation time. Such a decrease can be achieved by turbulization of the combustion zone or by introduction of metal powder, carbon black, or other particles having a high thermal conductivity. The vibrations can also be lowered by changing the design or the physicochemical properties to lower the decrement k - b, where

$$b = \gamma a = A_1 \omega^2 + a_2 \omega^{1/2},$$

$$k = \frac{\omega}{\pi r} \frac{Q_1 \omega^2 - Q_2}{Q_1 \omega^2 + Q_2},$$

$$Q_1 = \frac{a_2^4}{a_1^4} \tau^2; \quad Q_2 = (\varkappa - 1)^2 \eta^2 \xi^2; \quad \eta = \frac{h_m}{a_1^2}; \quad \xi = \frac{\varepsilon}{RT_2}.$$

The following notation was used in the formula: a = acoustic velocity; γ = coefficient of wave absorption; $\mu = h_m . w/p . R$; $\varkappa = c_p/\omega$; h_m = heat of reaction; ε = activation energy; z = width of combustion zone; T = temperature; m = reaction order; ω_o = natural frequency; x = coordinate; P_i' = deviation of pressure from equilibrium; w = volumetric reaction rate; μ = boundary factor; and subscripts 1 and 2 refer to the fresh gas and combustion products, respectively.

21*) Artamov, K. I., and I. G. Krutikova. Thermoacoustic instability of a nonuniform gas flow. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Mekhanika i mashinostroyeniye, no. 3, 1962, 19-23.

The stability of one-dimensional gas flow with internal heat sources in a variable-area duct was analyzed for cases in which 1) the longitudinal temperature gradient in the duct is variable and 2) the temperature gradient is constant. In the first case the rate of heat input is proportional to the gas density. The oscillations are excited by interaction of the entropy waves with the pressure waves. The stability boundaries were calculated for this case in terms of three dimensionless parameters, the specific heat ratio (γ), the Mach number at the inlet (M_o), and a parameter (μ) which characterizes the ratio of the heat input to the initial heat content of the gas. Computer calculations were made for

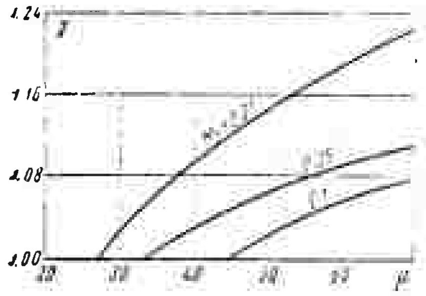


Fig. 18. Stability of one-dimensional gas flow with variable longitudinal temperature gradient

$0.01 << M << 0.1$; $1 << \gamma << 1.4$; and μ from 0 to 70. Fig. 18 shows the results obtained for this case.

The figure shows that the flow is stabilized when M_0 and γ increase and μ decreases. (The values of γ close to unity are useful for ionized or dissociated gas flow.)

For the second case (constant temperature gradient), when the rate of heat flow is proportional to the mass of gas in a given cross section, the calculations showed that instability does not occur in the range of parameters investigated, even at large values of μ (up to 200). This shows that a constant longitudinal temperature gradient has a strong stabilizing effect.

22*) Raushenbakh, B. V. Vibratsionnoye goreniye (Oscillatory combustion). Moskva, Fizmatgiz, 1961. 500 p.

Foreword (p. 7):

The book contains analyses of idealized systems (combustion in a cylindrical tube); the basic material presented is related to experiments of an academic nature (combustion of a mixture in a small tube, and behind a simple flame holder or without it; combustion in real furnaces, engines, etc., is not covered). In order to make the text plain to a wide engineering audience, the points considered are presented by the simplest methods and in sufficient detail; to understand the problems the normal preparation in mathematics and mechanics furnished by Soviet technical schools of higher education is therefore sufficient.

The book does not give a complete picture of the present-day state of the subject. It emphasizes primarily results obtained by the author, which have been published in part at various times in periodical literature. When contributions by other authors are utilized, footnotes are always given; their absence indicates that the results (whether theoretical or experimental) were obtained by the author. In addition to a number of contributions published previously, the basic material used for this book comprises lectures read to his students by the author during recent years at the Moscow Physicotechnical Institute.

Section 35. Feedback Mechanisms Based on Mixture Formation.

(p. 286):

Generally, various furnaces, engine combustion chambers, etc., contain as one of their main components a device for preparation of the fuel mixture. Not infrequently, such a device is made in the form of a nozzle to atomize fuel before the combustion zone. Certain other designs are sometimes also used. Regardless of the device used to prepare the fuel mixture, mixture formation can substantially effect the combustion process; in particular, there may be an effect on the excitation of oscillatory combustion. This fact is most easily shown by considering the following. A certain nonuniformity may be a characteristic feature of gas formation; if, in addition, this nonuniformity is also of a periodic nature, then the mixture reaching the combustion zone has an air-excess coefficient which varies periodically, or the ratios between the fuel in the liquid and vapor phases, etc., vary periodically. This can lead to the occurrence of oscillatory heat release as well as fluctuations of the flame front, and, consequently, to sustaining of the oscillations. It is advisable to express the above general considerations in a somewhat more concrete form by describing in greater detail the typical mechanisms connected with the mixture-formation process which sustains the oscillations.

(p. 294):

It would appear that by shifting the collector slightly, a location could be selected at which the oscillations would be suppressed. [Oscillations caused by nonuniform fuel or air injection rates can be suppressed by shifting the fuel injector in an axial direction to the optimum position].

(p. 296):

To summarize the content of this section, it should be pointed out that even the small number of examples given make it possible to claim that the mixture-formation process could become the basis for the appearance of a number of feedback mechanisms. It is quite clear that the individual mechanisms described which are connected with the variations in fuel feed rate, with a change in the air-excess coefficient, and with the quality of fuel atomization should most often occur simultaneously, since they all reflect the disturbance of the mixture-formation process. Of course, this does not mean that some phase of the process examined cannot play a leading role in some concrete case; this is why it is correct to describe the various phases of the single process of disturbed-mixture formation by independent feedback mechanisms. The feature common to all these mechanisms is the presence of a delay connected with the time required for the flow to carry the atomized fuel to the combustion zone. This delay becomes zero only when fuel is fed directly into the combustion zone.

Section 36. <u>Feedback Mechanisms Based on Hydromechanical Phenomena</u>.

(pp. 296-297):

If mixture formation were the only process by which a certain feedback mechanism could be accomplished, overcoming oscillatory combustion would be an extremely simple task. It would then be sufficient to prepare the fuel mixture in a separate vessel, acoustically isolated from the combustion chamber, in order to eliminate the appearance of oscillatory combustion. However, direct experiments disprove this. For instance, experiments were conducted with the excitation of oscillatory combustion in a tube into which a premixed gasoline-air mixture was injected. The mixture was prepared in a separate vessel. The gap between the tube containing the combustion zone and the nozzle feeding the gasoline-air mixture exceeded the tube's diameter. In addition, the mixture-feed tube had a larger diameter than the tube containing the combustion chamber. As a result of all this, the oscillations taking place in the combustion-chamber tube were in no way transmitted to the vessel in which the nozzles were located and the mixture prepared. This was confirmed by direct measurements of pressure oscillations in the vessel. Thus, any possible interaction between the acoustic oscillations in the tube and the formation of the mixture in the vessel was completely eliminated. Nevertheless, oscillatory combustion did appear.

It follows that processes other than mixture formation can exist which make the generation of feedback possible. A number of such processes can be grouped together on the basis of the fact that they all are connected with hydrodynamical processes in the gas traveling through the tube. This group of feedback mechanisms is based on the fact that acoustic oscillations, appearing during combustion, change substantially the nature of flow by imparting a periodical component.

(pp. 301-302):

Two methods of combating oscillatory combustion connected with hydrodynamical phenomena are feasible. A positive effect can be expected either if the phase of vortex separation is changed or if its dimensions are reduced. Concerning the first method, it should be said that it is very difficult to influence the phase of such a complex phenomenon as vortex separation. If the other method is chosen, then a simple design arrangement, i.e., the provision of flow-rectifying grids in the vortex path, can substantially affect the oscillatory combustion process. As is generally known, the grids are employed in those cases where it is found necessary to stabilize the flow, i.e., to impart to all its streams a direction parallel to the tube walls. The grid is an assembly of thin plates, usually intersecting each other at right angles, fitted in any tube section in such a way that the planes of the plate are parallel to the flow axis. Usually, it is sufficient to install two such grids, in a consecutive order, leaving a certain distance between them. These grids can have a low hydraulic resistance and cause no substantial change in the nature of the flow other than a stabilizing effect. Large vortexes, flowing through the grid, are actually sliced by the grid into many smaller vortexes. As a result, instead of a single large vortex, which could strongly distort the surface of the flame front, a cluster of many small vortexes reaches the combustion zone; as a result of the action of these small vortexes, the flame does not distort the flame surface, since it merely resembles a flow having a somewhat increased turbulence. Although the combustion process depends also on the turbulence of the incident flow, the dependence is in no way commensurable with the strong distortions of flame-front structure caused by large vortexes.

The general considerations discussed above were confirmed by special experiments.

(p. 304):

In the described experiment with grids (and in a number of others), the beneficial effect of breaking the interaction between vortex formation before the combustion zone and the combustion process has been clearly proved.

(pp. 304-305):

There are no general, standard methods for combating oscillatory combustion appearing in connection with vortex formation in the cool portion of the flow. In each concrete case, the source of vortex formation must be found, and suitable steps taken. This can sometimes be accomplished by installing grids or streamlining the bodies, or in other cases, by the use of guiding devices (e.g., guide vanes when the flow changes direction sharply), boundary-layer suction, or other measures, which have been well elaborated by experimental aerodynamics.

(pp. 310-311):

An interaction between the combustion process and the two types of vortex-formation (before the combustion zone and behind the flame holder) is quite possible. In this connection, the following experiment can be informative. The combustion of a premixed combustible mixture was carried out in a tube with a square corss section to study the two-dimensional combustion problem. The flame was stabilized by a flame holder, located in the middle of the flow and made in the form of a horizontal angular profile with the edge facing the flow. A rectangular baffle was placed close to the front of the flame holder, covering half of the rectangular cross section of the combustion chamber (the baffle adjoined one wall). Though placed close to the flame holder, the baffle was located outside the combustion zone. The baffle could be arranged horizontally or vertically. In the first position, its edge was parallel to the flame-holder edges; in the second position, it was perpendicular to them. Basically, the experiments consisted in the excitation of oscillatory combustion in this system, with measurements being taken of frequencies and amplitudes of pressure oscillations. The results of the experiments showed that with the baffle in vertical position the frequencies remained identical with those when the baffle plate was turned parallel to the flow, but the oscillation amplitudes, diminished. The change in the position of the baffle plate to horizontal resulted in a twofold decrease in the oscillation frequency, and in an increase of the oscillation amplitude. Such a result is natural if oscillatory combustion is explained by the processes connected with vortex formation: in the first case, one-half of the flame holder became "shaded," and thus the intensity of the total vortex-formation process became lower; in the second case, the baffle plate and flame holder could interfere with each other, which resulted in an increase in the intensity of vortex formation as well as in a change in the frequency of separation of vortexes. The latter resulted in the excitation of the second harmonic of the system; this harmonic agreed better with the new pattern of vortex formation.

(p. 312):

In conclusion, let us now briefly discuss the methods of combating oscillatory combustion (if it is undesirable) in the case when feedback is closed through vortex formation. As stated above, if the vortex-generating source is in front of the combustion zone, then the installation of grids and other similar measures may prove to be useful; the problem becomes more complicated if oscillations are excited by vortex formation behind the flame holder. The formation of these vortexes must not be eliminated since the presence of the recirculation flow zone behind the flame holder is a necessary condition for the operation of the flame holder as an ignition source. In this case, something could be done by empiric selection of the most suitable geometric configuration of flame holders.

There are indications in the literature that oscillatory combustion, which sometimes appears in industrial furnaces, is connected not only with the disturbance of fuel feed rate but also with the formation of strong regular vortexes in the region where fuel is fed to the combustion zone. In cases where oscillatory combustion is undesirable, rounding off of sharp edges, and other measures which would perfect the aerodynamic contours of the important sections of the furnace, are recommended. This practical point can be better understood in the light of the above considerations.

It is of interest that in the descriptions of the vortex formation in furnaces, it is emphasized (in connection with the pulsed nature of combustion) that the vortex in which combustion takes place has a tendency to become especially strong. Something similar was also observed in the above-described experiments with vortex formation behind flame holders during oscillatory combustion. It should be mentioned, however, that the problem of the effect of combustion in a vortex on its properties is not yet fully understood.

Section 44. Developmental Stages of the Oscillatory Combustion Process.

(p. 376):

As indicated above, oscillatory combustion is a typical self-oscillatory process. At the moment when the necessary conditions are reached, a sharp, practically instantaneous jump alters the amplitudes of the oscillations. Study of the developmental stages of this process is made very difficult by the rapid onset of oscillatory combustion (usually, oscillatory combustion reaches a steady amplitude within an interval of time equalling 2—3 oscillation periods). However, in some instances, when experiments are conducted with special laboratory-type setups, one can succeed in tracing the transitions from one steady self-oscillatory pattern to the other during the gradual change in the experimental conditions (air-excess coefficient and location of the movable flame holder along the flow axis). One can usually notice that different amplitudes correspond to different self-oscillatory patterns.

Section 47. Excitation and Suppression of Oscillatory Combustion.

(pp. 403-404):

The suppression of oscillatory combustion, if it has already developed, is a more intricate task. In some instances, it proves to be enough to break the feedback in the system. This could be done if the feedback mechanism which permitted the occurrence of oscillatory combustion is known. Examples of such types were given earlier, in the description of possible feedback mechanisms. To suppress oscillatory combustion when it appears as a result of the interaction between acoustic oscillations and the vortex-formation process before the combustion zone, it is sufficient to install grids between the point where vortexes have developed and the combustion zone. In other cases, methods should be used which would make it possible to break the pertinent patterns of feedback.

In order to employ the method outlined for fighting oscillatory combustion, very great difficulties have to be overcome. There are many feasible feedback mechanisms, and they may be of quite different physical nature. Therefore, in attempting to break the dangerous feedback, one may actually be compelled to break all possible feedbacks. Since it is not always possible to guess the most dangerous feedback under given concrete conditions, one is necessarily limited to a consideration of the most general requirements only: to establish a constant fuel flow, and to see that all the outlines of the tube in the inlet section, etc., are smooth. However, even when all these requirements are met, there remains the possibility that the processes connected with the influence of variable accelerations on the flame front, etc., could appear.

(pp. 404-406):

Oscillatory combustion can be effectively suppressed if multipurpose methods are used, e.g., those which exert an identical effect on all or at least on the majority of the feedback mechanisms, or on the oscillatory system as a whole.

The most natural multipurpose method of fighting oscillatory combustion is by increasing the acoustic-energy losses. This can be done by designing some sort of acoustic-pulse damping system in the end sections. This measure is not always feasible, since hydraulic losses could then appear, or it may interfere with other requirements. If the inclusion of damping devices in the structure of the tube end sections is undesirable, such radical measure as, e.g., a longitudinal slot in the tube body, may be suggested; the slot (or closely spaced boreholes along one of the generatrices) would make it possible for the gases inside the tube to flow outside and to bypass the end sections. This measure would be almost impossible if the pressure inside the tube considerably exceeded the ambient pressure.

In some cases it would perhaps be useful to equip the internal walls of the tube with acoustic dampers similar to those used for soundproofing dwellings. However, it should be noted that while direct experimental data on the damping effect of acoustic-energy absorbers in end sections and of boreholes in the tube body are available, there are as yet no known experiments dealing with the utilization of acoustically damping tube walls.

The above-enumerated methods for direct damping of oscillations are, generally, effective and sufficiently universal (they do not depend on the concrete kind of feedback mechanism). These methods are often impracticable because of design requirements connected with hydraulic resistance, cooling of the tube, etc. Therefore, it is more desirable to develop multipurpose methods for suppressing oscillatory combustion by directly influencing the combustion zone, without changing the design of the tube and the structures connected with the tube ends.

Such a method, which could probably prove to be useful in many cases, is the arrangement of the combustion zone so as to extend it along the entire tube. Up to now, only cases were considered where the length of the heat-release zone (σ) was small. The general method of relating a nonsteady-combustion process in a given extent heat-release zone (σ), to the heat-release process in a plane of a strong discontinuity (Σ) was given in Chapter 4. However, this method has not been utilized for studying aspects (of a combustion process) which would make the self-excitation of an oscillatory system impossible.

(p. 412):

One should not believe that extending a combustion zone by the use of two combustion centers is useful only if the feedback mechanisms belong in the group connected with mixture formation. One could suppose that such phenomena as those connected with vortexes entering the combustion zone also disturb the combustion process, to a lesser extent, provided that they do not simultaneously influence the entire combustion zone which, in this case, has a considerable length.

(p. 413):

On the basis of the above considerations, one can maintain that the distribution of the combustion zone has a positive effect on the reduction of the amplitude of disturbance of the heat release.

(p. 415):

The combustion-zone structure can substantially affect the possibility of acoustic-oscillation excitation; the combustion, distributed along the tube axis, should display a reduced tendency to self-excitation of acoustic oscillations.

To sum up what was said about the characteristics of the extended arrangement of combustion, it may be maintained that such a combustion pattern could noticeably decrease the excitation amplitudes of heat release, as well as of the effective burning rate, and it is therefore a multipurpose method for combating oscillatory combustion.

As shown earlier, the excitation of acoustic oscillations in liquid-propellant rocket engines is not connected with the disturbance of the heat release or the effective burning rate, but rather with the disturbance in the gas formation at the combustion front. Nevertheless, the general conclusion that when the combustion pattern is extended, acoustic-oscillation excitation is less probable than in the case when combustion is concentrated in a single section is, to a certain extent, correct also for liquid-propellant rocket engines. This was indicated by Crocco and Cheng*, who examined the stability of longitudinal acoustic oscillations in liquid-propellant rocket engines, assuming

---

* Crocco, L., and S. I. Cheng. High-frequency combustion instability in a rocket engine with concentrated combustion. Journal of the Rocket Society, v. 23, no. 5, 1953.

that combustion is concentrated in two combustion fronts separated by a finite distance. When these two fronts were arranged in the necessary positions (one at the combustion chamber head, i.e., at the antinode of pressure, and the other at the pressure node) this resulted in the reduction of the probability of excitation of the system. Consequently, extended combustion (combustion in two fronts) could also show a damping influence of the self-excitation process of longitudinal acoustic oscillations in liquid-propellant rocket engines.

The extended combustion pattern ers from the conventional one by the development of two or more at-release planes instead of a single one. It is conceivable to change the combustion pattern in a transverse direction as well. For instance, it is possible to heat only that portion of gas which passes through the heat-release region, the other portion remaining cool. Behind the heat-release zone, a flow with parallel streams develops, some of which are heated, while others have a temperature equal to that of the gas in front of the heat-release zone. If these streams do not mix in the immediate vicinity of the heat source, then such a stratified flow structure behind the heat-release area could also contribute to the damping of oscillations.

Section 51. Oscillatory Combustion in Ramjet Engines.

(pp. 467-469):

Among the various types of reaction engines used in modern engineering, ramjet engines have a definite range of use. Their distinctive features are, first, that air is used in burning the fuel and, secondly, that the pressure of this air is not raised in compressors with a mechanical drive. When a ramjet travels through the air, the incident air enters a diffuser where it is slowed down and the pressure increases. The combustion chamber, with an outlet nozzle at its end, is behind the diffuser. The fuel injector delivering fuel into the air, and the flame holder, are located in the combustion chamber. As seen from this brief description, the idealized layout of a ramjet engine can be represented by a tube, in which intensive combustion takes place in the region of the flame holder. A more detailed description of the design, the principles of operation, and other characteristics of such engines, can be found in special manuals, e.g., in the book written by M. M. Bondaryuk and S. M. Il'yashenko*.

These authors point out in their book that oscillations are sometimes observed in ramjet engines during tests, and that the oscillations have an acoustic frequency which is characteristic for the engine as a whole.

---

* Pryamotochnyye vozdushno-reaktivnyye dvigateli. Oborongiz, Moscow, 1958.

It has been the accepted practice not to single out the unavoidable small, irregular oscillations of pressure and velocity appearing during combustion of fuel and use the term "undisturbed" combustion for such a process. If, however, the amplitudes of pressure oscillations increase severalfold (but remain substantially lower than the mean pressure inthe chamber), and the frequency becomes regular, the accepted term qualifying such a combustion regime is "hard". When the pressure oscillations reach the level of the order of mean pressure in the combustion chamber, the oscillations being regular, then the combustion is described as "pulsed". M. M. Bondaryuk and S. M. Il'yashenko gave the typical pressure oscillograms for these cases and pointed out that "hard" and "pulsed" pressure fluctuations are not permissible in engines because they could cause disintegration of certain parts of the structure.

It is obvious that in the case considered acoustic oscillations are excited by combustion. An intensive heat-release zone, located in the flame-holder region, can excite longitudinal acoustic oscillations of the gas column between the inlet cross section of the diffuser and the nozzle outlet cross section. For this, as was stated earlier, it is necessary that the combustion phase (this notion includes both the heat release and displacement of the flame-front) be coupled with the oscillation phase of the gas column. In addition, a certain feedback mechanism should exist to generate the disturbance in the combustion process in the acoustic oscillations.

Section 52. Longitudinal Oscillations in Liquid-Propellant Rocket Engines.

(pp. 471-472):

During the operation of liquid-propellant engines, pressure oscillations in the combustion chamber, oscillations in fuel consumption, etc., are always present. This results in thrust oscillations, which are absorbed by the engine support structure in the form of mechanical vibrations. These vibrations are not at all dangerous to the structure and do not lower the engine's efficiency. They should be considered a natural occurrence such as vibration and noise in an automobile engine. However, it was noticed that under certain conditions, the irregular oscillations change their nature sharply. Their amplitude rises considerably, and they become highly dangerous for the engine structure. Therefore, the requirements which should be met for satisfactory development of rocket engineering resulted in the necessity for detailed investigation of self-oscillations in combustion chambers of liquid-propellant rocket engines. A number of articles on this problem appeared in periodical literature and, recently, a very valuable monograph by Luigi Crocco and S. I. Cheng was published.*

(p. 472):

The low-frequency oscillations are caused by the occurrence of instability in the system which comprises the combustion chamber and fuel-feed system. The mechanism underlying the generation of instability depends on the effect of the periodical pressure oscillations in the combustion chamber on the fuel feed rate and on the ignition delay time. A characteristic feature of this type of self-oscillation is the fact that, in investigating it, one can disregard the length of the combustion chamber and consider it as a certain gas volume with a pressure which changes in every cross section in the same way.

The high-frequency oscillations are also caused by the occurrence of instability considered by small disturbances, and, in this case, the interaction between the pressure oscillations in the combustion chamber and the process of preparation and ignition of the fuel mixture also plays a decisive role. However, the length of the combustion chamber cannot be disregarded in this case (as it was in the previous case), and it should not be assumed that pressure and other parameters change identically in all the cross sections of the combustion chamber.

From the mechanical standpoint, the first case is in many ways analogous to the common dynamic systems (defined by ordinary differential equations), while the second case is associated with the propagation of disturbances in a continuous medium, i.e., with acoustic-type phenomena (defined by differential equations with partial derivatives).

(p. 474):

Combustion in the engine depends most strongly on the processes taking place at the engine head. Since liquid components are injected into the combustion chamber, mixture formation therefore plays a highly important role. The effectiveness and rapidity of combustion of the injected fuel depends on the quality of atomization and mixing of components (if it is not a single-component fuel), on the rate of evaporation of fuel droplets, and on the heating of the fuel mixture. These combined processes require a certain time for their completion; only after this time has elapsed can an intense chemical reaction take place.

---

* Theory of Combustion Instability in Liquid Propellant Rocket Motors. Butterworth Scientific Publications, 1956. Russian translation: Luidzhi Krokko i Chzhen Sin'-I. Teoriya neustoychivosti goreniya v zhidkostnykh reaktivnykh dvigatelyakh. Izd-vo inostr. literatury, Moscow, 1958.

(p. 488):

Examination of the stability diagrams makes it obvious that excitation of the system cannot take place if the combustion front is located in the pressure node, even in the case when (e.g., under the influence of velocity oscillation) gas formation has an oscillatory component other than zero.

(p. 491):

When the stability diagram was discussed, it was stated that excitation of the system is impossible in the pressure node. Therefore, the problem of the tendency of the examined oscillatory system to self-excitation, depending on the location of the combustion front along the engine combustion chamber, should be analyzed in more detail.

(p. 495-497):

For the first harmonic, instability will occur in two cases: when the combustion front is at the [engine] head and when it is at the nozzle.

(pp. 495-496):

If the process in the combustion chamber has a tendency to oscillatory combustion, the latter should appear independently of the location of the combustion zone along the length of the combustion chamber. The only difference is that, depending on the coordinate of the combustion front, $0 < \xi_\varphi < 1$, one or the other harmonic could become excited.

(pp. 496-497):

In this section, only an elementary exposition is given of the theory of high-frequency longitudinal acoustic oscillations in liquid-propellant rocket engines. Those interested in a more complete exposition of the problem are advised to consult the monograph by Crocco and Cheng, mentioned previously and pertinent articles in the periodical literature.

With this last statement we conclude the present section. In all previous chapters it was repeatedly emphasized that, as a final result, the disturbance of heat release or of effective burning rate is the cause of the excitation of oscillatory combustion. In the case of the excitation of acoustic oscillations in liquid-propellant rocket engines, the main disturbance is that of gas formation (the disturbance of the consumption of a certain mass source located in the combustion zone). Consequently, oscillatory combustion can have a most diverse nature. In the general case, it can become excited by any component contained in the [equation] system (15.5) [p. 120] and defining the process taking place inside the region δ. This [component] can be δM^* (the case just considered), δQ^*, themobility of the flame front, i.e., the non-equality with zero of the partial derivatives (contained in all the three equations) from integrals over volume V (the case considered in Section 49), and the disturbance of the calorific value ofmixture δq, and of completeness of combustion, $\delta q_1 - \delta q_2$ (the example given in Section 25). Finally, the excitation of acoustic oscillations can be found to be connected with the difference from zero of the component δP_x. Such a process is set up, e.g., in the cases when vortexes are periodically separated in the zone δ. The interaction between the vortex formation and the acoustic oscillations could then result in self-excitation of the oscillatory system. Since this case is not at all connected with the combustion process, it is not examined in this book.

Such a diversity of causes of excitation of longitudinal acoustic oscillations requires amost careful analysis of all the variables contained in the system (15.5) before an idealized scheme for an unstable combustion process is selected.

23*) Zaydel', R. M. Possibility of stable combustion. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 5, 1962, 80-82.

The inequality $\rho_1/\rho_2 < 3$, ρ_1 and ρ_2 being the densities of the fresh gas mixture and the combustion products, respectively, has been derived by analysis of the induction-controlled operating regime as a criterion for combustion stability in the presence of small perturbations passing through the flame front. This regime was recently defined by Zaydel' and Zeldovich as one of the possible operating regimes established in [rocket] combustion chambers as a function of feed gas velocity. The stability criterion can also be expressed in the form:

$$\frac{\gamma_1(\gamma_2 - 1)}{\gamma_2(\gamma_1 - 1)}\left[(\gamma_1 - 1)\frac{q}{c_1^2} + 1\right] < 3,$$

where γ_1 and γ_2 are the isentropic exponents of fresn gas and combustion products, respectively, q is the heat content, and c_1 is the acoustic velocity in the fresh gas. L. D. Landau's stability analysis was followed in part; the gas upstream and downstream of the discontinuity were considered incompressible, the viscosity was neglected, and the wavelength of the perturbation was assumed small in relation to the chamber dimension and the distance of the flame front from the chamber head. Since only small perturbations were considered, the criterion derived is a necessary but generally not sufficient condition for combustion stability. The boundary conditions at the chamber head and the side walls must be analyzed in detail in order to obtain

criteria for combustion stability in the presence of longwave perturbations.

25*) Korobkova, M. P. Rate of heat release at the limits of oscillatory combustion. Inzhenerno-fizicheskiy zhurnal, no. 11, 1961, 64-67.

The effect of inert admixtures on oscillatory combustion in tubes was studied previously by S. A. Abukov (Tret'ye vsesoyuznoe soveshchaniye po teorii goreniya, 1, 44, Moscow 1960). The regions in which oscillations occur in the combustion of CO-air mixtures containing CO_2, N_2, or Ar were determined in this study. It was assumed that oscillatory combustion is a self-oscillating process and that at the concentration limits at which oscillatory combustion occurs the heat release rate remains unchanged for any combustible composition. This assumption was verified by Korobkova, who studied oscillatory combustion of CO-air, hydrocarbon gas-air, and propane-air mixtures containing varying amounts of N_2 or CO_2, in a tube 3 cm in diameter and 85 cm long. The heat-release rate was obtained by methods 1) calculating the chemical reaction rate and 2) measuring the normal burning velocity. The following relationships were used in the study: 1) The heat release rate is proportional to the chemical reaction rate, and 2) the maximum chemical reaction rate is proportional to the square of the normal burning velocity.

26*) Kurzhunov, V. V. Some experimental data on the effect of pressure on oscillatory combustion in tubes. Inzhernerno-fizicheskiy zhurnal, no. 7, 1964, 91-95.

A study was made with CO-air, acetylene-air, and propane-air mixtures in a semi-enclosed cylindrical glass tube to determine the effect of pressure on the limits of oscillatory combustion. The open end of the tube was connected to a large-diameter vessel which was evacuated to low pressure to simulate outer atmospheric conditions. All experiments were conducted at reduced pressure, and the process was scanned by motion picture photography. Fig. 19 shows the concentration limits of oscillatory combustion as a function of composition (A = air excess factor expressing the air fuel ratio). The figure shows that a change in initial gas temperature causes a shift of the boundary curve. Figs. 20 and 21 show the amplitude and frequency of oscillations of the flame front as functions of pressure. Fig. 22 shows the minimum tube length (L_{min}) at which oscillatory combustion occurs as a function of pressure. All experiments refer to longitudinal oscillations. Osborn and Bonnell found that at high pressures the chamber parameters affect the transverse oscillations in a manner opposite to that found in this study.

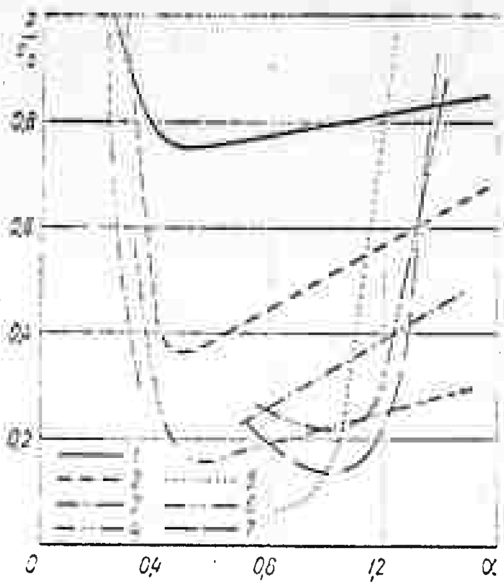


Fig. 19. Limits of oscillatory burning

1 - CO, T_0 = 550°K, R = 0.01 m, L = 0.47 m; 2 - CO, T_0 = 293°K, R = 0.01 m, L = 0.47 m; 3 - CO, T_0 = 293°K, R = 0.005 m, L = 1.1 m; 4 - CO, T_0 = 550°K, R = 0.01 m, L = 1.1 m; 5 - C_2H_2, T_0 = 550°K, R = 0.005 m, L = 1.1 m, 6 - C_3H_8, T_0 = 550°K, R = 0.01 m, L = 0.47 m; 7 - C_3H_8, T_0 = 293°K, R = 0.01, L = 0.47 m. R - tube diameter; T_0 - initial temperature; L - tube length.

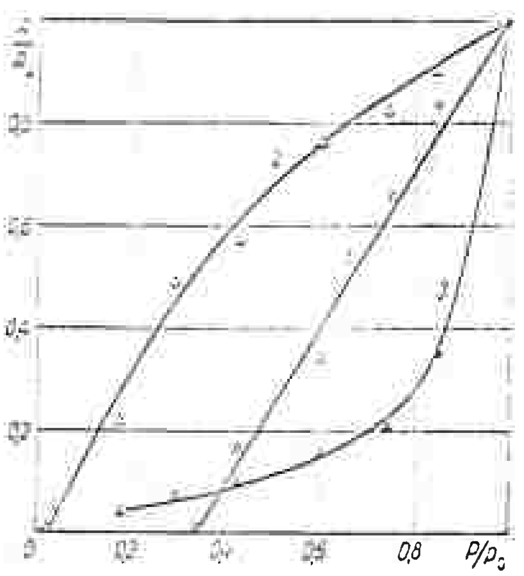


Fig. 20. Amplitudes of flame-front oscillations as a function of pressure

1 - CO, α = 0.43, T_0 = 293°K, R = 0.01 m, L = 0.47 m; 2 - C_2H_2, α = 1.58, T_0 = 550°K, R = 0.01 m, L = 0.47; 3 - C_3H_8, α = 0.48, T_0 = 293°K, R = 0.005 m, L = 1.1 m.

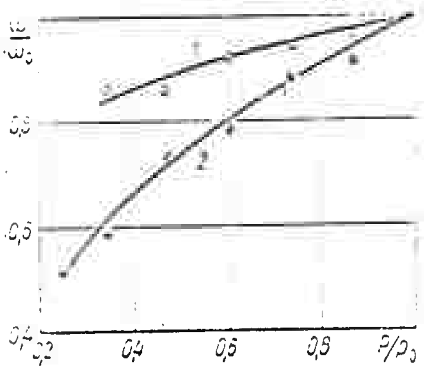


Fig. 21. Effect of pressure on frequency of flame front oscillations

1 - T_0 = 550°K; 2 - T_0 = 293°K; CO, α = 0.65, R = 0.01 m, L = 1.1 m.

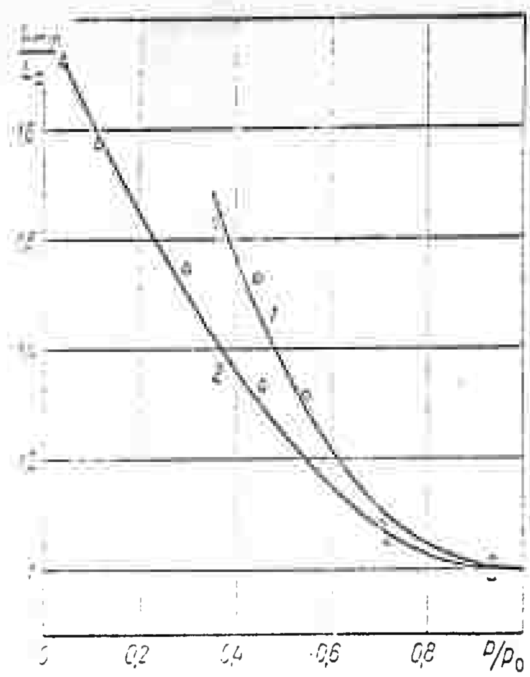


Fig. 22. Dependence of L_{min} on pressure

1 - CO, α = 0.65; 2 - C_3H_8, α = 0.48; T_0 = 293°K, R = 0.01 m.

27*) Kurzhunov, V. V. Effect of pressure on oscillatory combustion in tubes. Inzhenerno-fizicheskiy zhurnal, no. 2, 1964, 103-107.

A theoretical analysis of the effect of pressure on the limits of oscillatory combustion in tubes was made, on the basis of an energy balance, in terms of the flame-generated acoustic energy and the energy dissipated in the tube. A generalized expression for determining the pressure above which oscillatory combustion is possible was obtained. Some conclusions were drawn concerning the effect of pressure, composition, and tube parameters on longitudinal oscillations. For instance, the amplitude increases as the difference between generated and dissipated energy increases. The amplitude also increases with increasing pressure and at constant pressure with increasing normal burning velocity, tube length (for the case $d/L \to 1$) and tube diameter (for the case $d/L \ll 1$). An increase in tube diameter at $d/L \to 1$ leads to a rapid decrease in amplitude. The effect of pressure on the critical tube length was also discussed.

28*) Zaydel', R. M. and Ya. B. Zel'dovich. Possible operating regimes in steady-state combustion. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 4, 1962, 27-32.

Because the fuel in modern combustion engines, e.g., rocket motors, is preheated prior to injection into the combustion chamber, with the result that the reaction rate at the injection point is not zero, the unburned fuel in the chamber is heated by heat conduction from the hot combustion products as well as by a self-accelerating fuel-temperature increase. Depending on the relation between these two heating processes, which are controlled mainly by the initial temperature and the injection velocity of the fuel, combustion can take place under various regimes characterized by the distance of the flame front from the injection point. This problem is analyzed, and axial temperature and concentration profiles in terms of dimensionless parameters are obtained by solution of the heat- and mass-transfer equations for steady-state combustion. Plots of

$$z = \frac{T - T_0}{T_{max} - T_0}$$

versus x/L = distance parameter and of x/L versus $\alpha = \chi/\tau u^2$, where τ = thermal conductivity, χ = induction period, and u = injection velocity, are presented. It is shown that when the chamber is operated at an injection velocity corresponding to $\alpha = 1.1$, an increase in injection speed by a factor of 2.5 would make $\alpha < 0.2$, i.e., an induction-controlled regime would be established. An intermediate regime is obtained in the range $0.2 < \alpha < 1.1$.

31*) Raushenbakh, B. V., S. A. Belyy, I. V. Bespalov, V. Ya. Borodachev, M. S. Volynskiy, and A. G. Prudnikov. Some recommendations for fighting oscillatory combustion. IN THEIR: Fizicheskiye osnovy rabochego protsessa v kamerach sgoraniya vozdushno-reaktivnykh dvigateley (Physical principles of the operating process of jet-engine combustion chambers). Moskva, Izd-vo AN SSSR, 1964. 369-370.

In order to obtain self-excited oscillations, a feedback is required which would result in the proper amplitude and phase relationships. A theoretical result was given above in accordance with which an oscillatory system could become self-excited only if the disturbance δQ (perturbation of the heat release rate) is adequately shifted phasewise with reference to δp_1 (perturbation of pressure) and its relative magnitude is large enough. The self-excitation process due to the disturbance δu_{cr} (perturbation of the effective burning velocity) takes place under identical laws. Thus, generally speaking, oscillatory vibrations may be combated by changing either the oscillation phase of δQ and δu_{cr} or their relative amplitudes.

Basically, the first method requires exerting an influence on the oscillation phase. If, for instance, the feedback was coupled as a result of the oscillation of the air flow rate, the phase of the entry of the enriched mixture into the combustion zone could be changes by displacing the fuel injector along the flow axis. In other cases , other measures should be taken, sometimes similarly simple ones. However, experience with combustion chambers shows that such methods do not give noticeable results. Attempts to influence the induction period (ignition delay) or to rearrange the flame front did not give noticeable results either. In general, influencing processes associated with the oscillation phase rarely gives positive results.

The second method consists in influencing the relative amplitudes δQ and δu_{cr}. If $/\delta Q/$ and $/\delta u_{cr}/$ are reduced to a very small value, oscillatory combustion will be terminated, regardless of the phase relationships. It follows that oscillatory combustion should be combated by reducing the relative amplitudes of the effective heat release and the effective burning velocity, rather than by influencing the phase relationships. The combustion process should be influenced in such a way as to decrease the relative amplitudes δQ and δu_{cr} as much as possible, regardless of the feedback mechanism (which is often unknown). It has been shown in practice that the best methods for reducing $/\delta Q/$ and δu_{cr} are those in which the measures taken consist in distribution of combustion, illustrated in the following example (see Fig. 23).

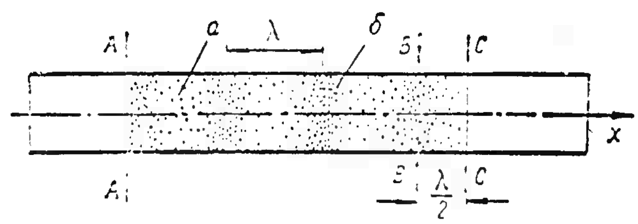


Fig. 23. Diagram of distributed combustion

B-B and C-C - Regions where flame holders are installed (a - lean mixture; δ - enriched mixture).

The length of the perturbation wave α (distance between adjacent regions of enriched mixture) equals λ. Combustion starts in cross section B-B. If two combustion centers are formed (e.g., by locating flame holders in two cross sections), the distance between the centers is $\lambda/2$, and the combustion process would have the following distinguishing feature. Let these two centers be located in cross sections B-B and C-C. While an enriched mixture is in the first cross section, there is, at the same moment, a lean mixture in the second cross section. As a result, if the mixture, with $\alpha > 1$, is burning, the total heat release is near the nonexcited level because the excess heat, produced in cross section B-B, would compensate for the heat deficiency in the cross section C-C. During a time interval equal to one-half of an oscillation period, the lean and enriched mixtures are in B-B and C-C, respectively, i.e., the smoothing process of the amplitudes of heat-release perturbation will continue. Thus, this simple procedure can reduce $/\delta Q/$ considerably.

This example refers to a particular case, but analogous considerations can be presented for a number of other feedback mechanisms as well. Experiments have confirmed that distribution of the combustion zone is a sufficiently universal measure for fighting oscillatory combustion.

32*) Solov'yev, V. V. Problem of oscillatory combustion in high-performance furnace chambers. Inzhenerno-fizicheskiy zhurnal, no. 1, 1959, 25-31.

Oscillatory combustion was studied in an experimental coal-dust combustion chamber. The frequency and amplitudes of the pressure oscillations and the luminosity pulsations were measured in different sections of the chamber. The theoretical treatment was based on Raushenbakh's earlier studies. Formulas were derived to calculate σ and ν, and the stability diagram shown in Fig. 24 was obtained.

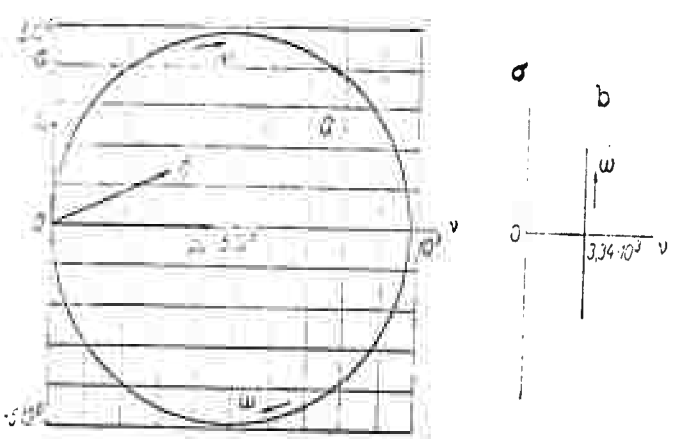


Fig. 24. Stability limits for a chamber 1.4 m in diameter and 7 m long at $z = 0$ (a), and near the origin of the coordinates (b)

z - Acoustic impedance; p - pressure; q - heat release rate; $q = \mu p_1$ and $\mu = \nu + i\sigma$.

It was found that under the conditions studied oscillatory combustion was induced by the coincidence of the phases of p and q. This was probably caused by the ignition delay time of the aerosol.

33*) Dubrovskiy, O. V. Experimental investigation of oscillatory combustion of liquid fuel in combustion chambers of stationary gas turbine units. Teploenergetika, v. 6, no. 6, 1959, 56-61.

During operation of gas turbines, it has been found that the turbine power fluctuates with frequencies of 1.5—3 cycles per second. Oscillation amplitudes reached 15% of normal power level in individual cases. Subsequent experiments have shown that behind the combustion chamber, temperature and pressure oscillations of the gas flow take place.

To study oscillatory combustion, a combustion chamber with a two-stage swirler of primary air and with a register for injection of secondary cooling air was desinged (see Fig. 25). Two coaxial registers, one small and the other large (ensuring air feed to the combustion zone), and a cooling-air swirler were special features of the combustion chamber. All the swirlers had flat blades with radially arranged exit edges. Secondary air was mixed with the combustion products from the primary zone by an S-shaped mixer.

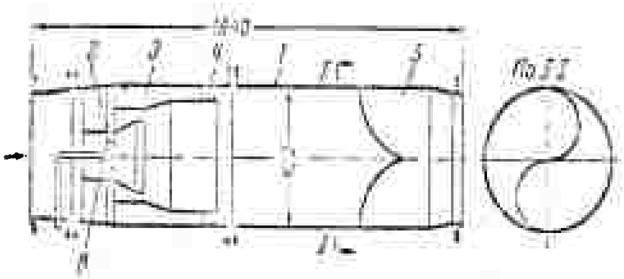


Fig. 25. Diagram of combustion chamber with two-stage swirler for primary air and register for secondary air

1 - Housing; 2 - small primary-air register; 3 - large primary-air register; 4 - secondary-air register, 5 - mixer; 6 - nozzle.

The temperature oscillations of gas behind the combustion chamber were recorded by a low-inertia resistance thermometer.

For measuring the flame luminosity fluctuations, ФС-К2 photocells were used.

The dependence of oscillatory-combustion characteristics on the operating conditions, which were changed over a fairly wide range, was determined during the experimental investigation. These ranges were: for the overall air-excess coefficient, 1.32 to 6.75; air temperature before the combustion chamber, 27 to 322°C; and the thermal load, 3.0×10^6 to 8.75×10^6 kcal/m^3 hr tech. atm.

Two types of oscillation processes were observed with the following frequency ranges: low frequency, 1.5—3.0 cps; medium frequency, 10—60 cps.

The frequency of low-frequency oscillations did not depend on the thermal load in the flame region. When the thermal load changed from 3.0 to 7.6 million kcal/m^3 hr tech. atm., the frequency level, remained unchanged (2.5 cps).

The experiments showed that the frequency level does not depend on the air temperature in front of the combustion chamber, and, therefore, that it does not depend on the duration of the preliminary stages of combustion. The only parameter which affects the low-frequency oscillations is the primary-air-excess coefficient (α_1) (Fig. 27). When this coefficient is increased, the frequency, other conditions being equal, decreased (when α_1 is increased from 1.6 to 5.5, the decrease is 2.5 to 1.25 cps). Simultaneously, this also causes an increase in hydraulic resistance in the combustion chamber.

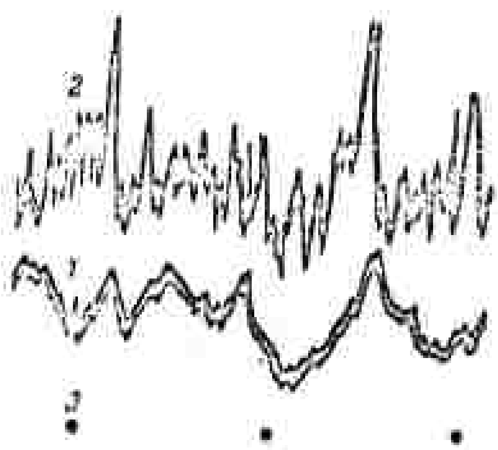


Fig. 26. Oscillograms of temperature and flame-luminosity oscillations

1 - Temperature oscillations; 2 - flame-luminosity oscillations; 3 - time marks.

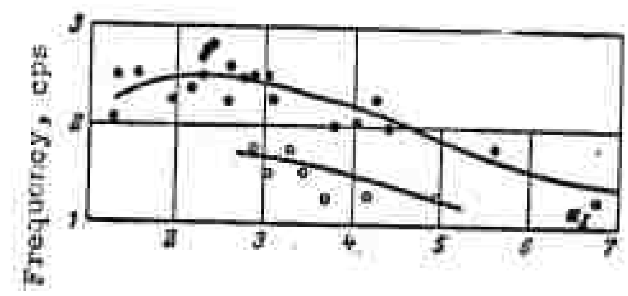


Fig. 27. Effect of air-excess coefficient on the frequency of low-frequency oscillations

The frequency of medium-frequency oscillations depends neither on thermal load in the flame region nor on the temperature of the air entering the combustion chamber. The level of these frequencies was found to be proportional to the consumption of primary air. The generalized pattern of this proportionality was established for the model as well as for the natural-size combustion chamber (Fig. 28).

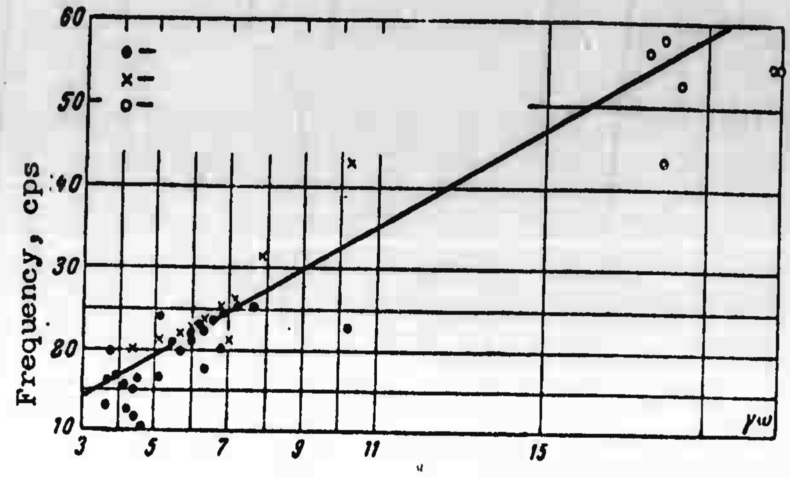


Fig. 28. Dependence of the frequency oscillations on mass velocity of primary air in the combustion region

• - Temperature oscillations in model; x - luminosity oscillations in model; o - temperature oscillations in combustion chamber of normal size.

Fuels having dissimilar physical properties, i.e., gasoline, solar oil, and having fuel oil, were used in the experiments. The results are shown in Fig. 29.

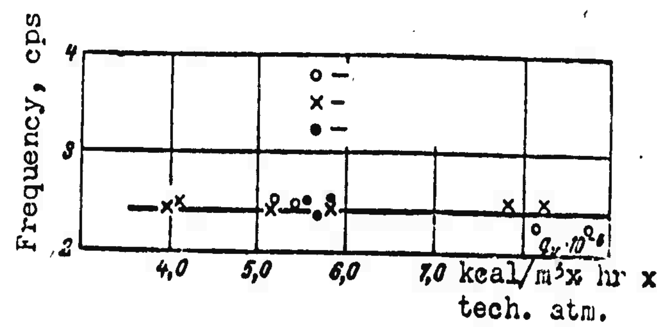


Fig. 29. Dependence of the frequency of low-frequency oscillations on the type of burned fuel

o - Gasoline; x - solar oil; • - heavy fuel oil.

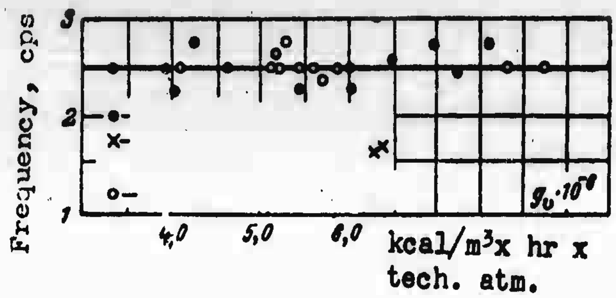


Fig. 30. Dependence of the frequency of low-frequency oscillations on the type of atomizer

• - Centrifugal nozzle; x - extended centrifugal nozzle; o - ejector nozzle.

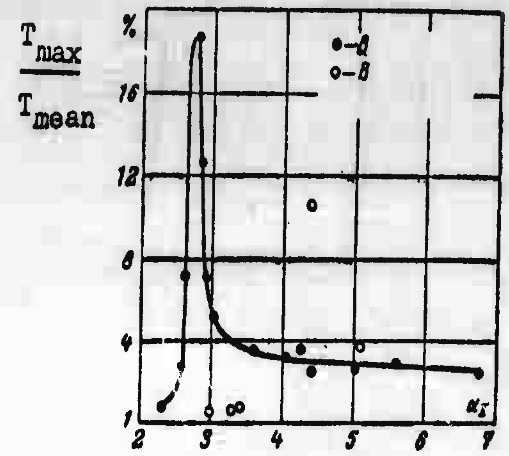


Fig. 31. Low-frequency oscillation amplitudes

• - In the model; o - in a chamber of normal size.

Conclusions:

1. When liquid fuel is burned in experimental or full-scale gas-turbine combustion chambers, oscillations of temperature and pressure behind the combustion chamber and oscillations of the flame luminosity are present; there are cyclic attenuated oscillations with an approximately constant amplitude.

2. The following two types of oscillation processes differing by the ranges of characteristic frequencies take place in the combustion chamber: low and medium frequencies of 1.5—3 and 10—60 cps, respectively.

3. The frequency of low-frequency oscillations does not depend on the following operating parameters: thermal load in the combustion zone, air temperature at the combustion-chamber inlet, primary-air consumption, liquid-fuel type, and atomizer type. The only parameter affecting the low-frequency level is the primary-air excess coefficient.

4. The frequency of medium-frequency oscillations rises with air-gas flow velocity. The medium-frequency oscillations are caused by oscillatory combustion of the fuel-air mixture which is nonuniformly distributed in the combustion-region.

5. In individual cases, the amplitudes of low-frequency oscillations may reach high values, and thus become harmful to the gas turbine.

34*) Trudy. 1-ya Vsesoyuznaya nauchno-tekhnicheskaya konferentsiya po probleme vibratsionnogo i pul'satsionnogo goreniya. Diskussiya (Discussion: Transactions of the First All-Union Scientific-Technical Conference on Problems of Oscillatory and Pulsating Combustion). Moskva, 1962. 44-46. TAKEN FROM: Referativnyy zhurnal. Mekhanika. Svodnyy tom., no. 12, 1963, 8. Abstract 12 B625.

The results are given of an experimental study on oscillatory combustion of a laminar hydrogen diffusion flame. Oscillatory combustion is induced if the volumetric consumption exceeds a certain critical value which depends on the mixture composition, tube parameter, and location of the flame. Oscillatory combustion is possible if the flame is within the linear excitation interval in the lower part of the tube. The value of the linear interval depends on the tube parameters, mixture composition, and gas consumption. The cause of oscillatory combustion, considered as a self-oscillating process, should be sought in the interaction between the oscillations of the gas in the tube and the flame proper. Toepler photographs showed periodical changes of the combustion products surrounding the flame which were in resonance with the oscillations of the gas column.

35*) Trudy. 1-ya Vsesoyuznaya nauchno-tekhnicheskaya konferentsiya po probleme vibratsionnogo i pul'satsionnogo goreniya. Diskussiya (Discussion: Transactions of the First All-Union Scientific-Technical Conference on Problems of Oscillatory and Pulsating Combustion). Moskva, 1962. 94-115. TAKEN FROM: Referativnyy zhurnal. Mekhanika. Svodnyy tom, no. 12, 1963, 98-99. Abstract 12 B626.

Discussion.

B. V. Raushenbakh has explained why the oscillatory component of mass flow, related to acoustic oscillations during oscillatory combustion, can reach considerable values. In his opinion, in a general case, oscillatory combustion is sustained not only by the oscillatory component of heat release but also by the oscillations of the effective rate of flame propagation.

Ya. S. Nazarovskiy stated that the most promising field for the utilization of vibrational combustion is heterogeneous rather than homogeneous combustion.

D. D. Ryzhov maintained that high-frequency oscillations of a flame are excited by the combustion region proper, owing to the excessive release of chemical energy during the interaction between the combustion region and small pressure disturbances.

B. M. Gun'ko treated intensification of combustion by pulsations, with emphasis on the processes by which valuable chemical products can be obtained.

V. A. Khristich stated that the change in the velocity of a chemical reaction plays a substantial role in the oscillation process.

A list of 266 titles of works on oscillation and pulsation combustion, compiled by O. G. Roginskiy and B. M. Gun'ko, is given at the end of the volume.

REFERENCES

1*) Salamandra, G. D., and O. A. Tsukhanova. Shock formation in front of the flame front. IN: Fizicheskaya gazodinamika (Physical gasdynamics). Moskva, Izd-vo AN SSSR, 1959. 151-162.

2) Salamandra, G. D., and I. K. Sevatyanova. Zhurnal tekhnicheskoy fiziki, 1959, v. 29, 1960.

3) Salamandra, G. D., T. V. Bazhenova, S. G. Zaitsev, R. I. Soloukhin, I. M. Naboko, and I. K. Sevyastyanova. Nekotarnyye metody issledovaniya bystroprotekayushikh protsessov i ikh primeneniye k izucheniyu formirovaniya delonatsionnoy volny (Some methods for investing high-speed processes and their application to the study of the development of detonation waves). Moskva, Izd-vo AN SSSR, 1960. 91 p.

4*) Salamandra, G. D. Interaction of flame with shock wave. IN: Fizicheskaya gazodinamika (Physical gasdynamics). Moskva, Izd-vo AN SSSR, 1959. 163-166.

5) Kogarko, S. M. Intensification of compression waves during interaction with the flame front. Zhurnal tekhnicheskoy fiziki, 1960, 30, 110.

6) Kogarko, S. M., and A. S. Novikov. Study of compression waves in combustion of gas mixtures. IN: Doklady. Akademiya nauk SSSR, 1960, 134, 125-127.

7*) Kogarko, S. M., and D. L. Ryzhkov. Study of the intensification of compression waves in combustion. Zhurnal tekhnicheskoy fiziki, v. 31, no. 2, 1961, 211-216.

8) Kogarko, S. M., and V. I. Skobelkin. Relaxational interaction of shock waves with the combustion zone. IN: Doklady. Akademiya nauk SSSR, v. 120, 1958, 1280.

9) Kogarko, S. M., V. I. Skobelkin, and A. N. Kazakov. Interaction between shock waves and the flame front. IN: Doklady. Akademiya nauk SSSR, 1958, v. 122, 1046-1048.

10*) Novikov, S. S., and Y. S. Ryazantsev. Interaction of weak pressure waves with the flame front. IN: Doklady. Akademiya nauk SSSR. 1961, v. 137, 1409-1412.

11) Shchelkin, K. I. A possible mechanism for intensifying weak shock waves in the zone of turbulent combustion. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Energetika i avtomatika, 1961, no. 5, 86.

12) Denisov, Yu. N., Ya. K. Troshin and I. I. Shchelkin. Analogy between combustion in a detonation wave and in a rocket engine. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Energetika i avtomatika, no. 6, 1959, 79-89.

13*) Salamandra, G. D., and I. K. Sevast'yanova. Intensification of shock wave during passage through flame front. IN: Fizicheskaya gazodinamika, teploobmen i termodinamika gazov vysokikh temperatur (Physical gasdynamics, heat transfer and thermodynamics of high-temperature gases). Moskva, Izd-vo AN SSSR, 1962. 199-203.

14*) Soloukhin, R. I. Shock wave refraction on a flame front. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 1963, 40-47.

15) Skobelkin, V. I. Relaxational interaction of shock waves with the flame front. Zhurnal fizicheskoy khimii, v. 36, no. 9, 1962, 1979-1986.

16*) Salamandra, G. D., and I. K. Sevastyanov. Formation of shock waves ahead of a flame front and their intensification during passage through the flame. Combustion and Flame, no. 2, 1963, 169-179.

17*) Kayushin, L. P. Effect of external friction and heat transfer on the motion of the ignition front and shock waves in chemically reactive media. IN: Gazodinamika i fizika goreniya (Gasdynamics and the physics of combustion). Moskva, Izd-vo AN SSSR, 1959. 57-68.

18*) Artamov, K. I. Stability of liquid-fuel rocket motor operation. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Mekhanika i mashinostroyeniye, no. 1, 1961, 64-69.

19*) Shchelkin, K. I., and Ya. Troshin. High-frequency oscillations in forced combustion chambers. IN: Gazodinamika goreniya (Gasdynamics of combustion). Moskva, Izd-vo AN SSSR, 1963. 215-238.

20*) Skobelkin, V. I. Theory of relaxational oscillations in a combustion chamber. Zhurnal tekhnicheskoy fiziki, no. 3, 1962, 346-355.

21*) Artamov, K. I., and I. G. Krutikova. Thermoacoustic instability of a nonuniform gas flow. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Mekhanika i mashinostroyeniye, no. 3, 1962, 19-23.

22*) Raushenbakh, B. V. Vibratsionnoye goreniye (Oscillatory combustion). Moskva, Fizmatgiz, 1961. 500 p.

23*) Zaydel', R. M. Possibility of stable combustion. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 5, 1962, 80-82.

24) Abukov, S. A. Tret'ye vsesoyuznoye soveshchaniye po teorii goreniya t. 1 (Third All-Union Conference on the Theory of Combustion, v. 1). Moskva, Izd-vo AN SSSR, 1960.

25*) Korobkova, M. P. Rate of heat release at the limits of oscillatory combustion. Inzhenerno-fizicheskiy zhurnal, no. 11, 1961, 64-67.

26*) Kurzhunov, V. V. Some experimental data on the effect of pressure on oscillatory combustion in tubes. Inzhenerno-fizicheskiy zhurnal, no. 7, 1964, 91-95.

27*) Kurzhunov, V. V. Effect of pressure on oscillatory combustion in tubes. Inzhenerno-fizicheskiy zhurnal, no. 2, 1964, 103-107.

28*) Zaydel', R. M., and Ya. B. Zel'dovich. Possible operating regimes in steady-state combustion. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 4, 1962, 27-32.

29) Basevich, V. Ya., M. K. Devishev, and S. M. Kogardko. Effect of active particles of combustion products on the speed of flame propagation in turbulent flow. IN: Izvestiya. Akademiya nauk SSSR. Otdeleniye tekhnicheskikh nauk. Energetika i avtomatika, no. 3, 1960, 138-144.

30) Kogarko, S. M., M. I. Devishev, and V. Ya. Basevich. Study on the effect of active particles of reaction products on combustion processes in flow. IN: Doklady. Akademiya nauk SSSR, v. 127, no. 1, 1959, 137-140.

31*) Raushenbakh, B. V., S. A. Belyy, I. V. Bespalov, V. Ya. Borodachev, M. S. Volynskiy, and A. G. Prudnikov. Some recommendations for fighting oscillatory combustion. IN THEIR: Fizicheskiye osnovy rabochego protsessa v kamerach sgoreniya vozdushno-reaktivnykh dvigateley (Physical principles of the operating process of jet-engine combustion chambers). Moskva, Izd-vo AN SSSR, 1964. 369-370.

32*) Solov'yev, V. V. Problem of oscillatory combustion in high-performance furnace chambers. Inzhenerno-fizicheskiy zhurnal, no. 1, 1959, 25-31.

33*) Dubrovskiy, O. V. Experimental investigation of oscillatory combustion of liquid fuel in combustion chambers of stationary gas turbines. Teploenergetika, v. 6, no. 6, 1959, 56-61.

34*) Trudy. 1-ya Vsesoyuznaya nauchno-tekhnicheskaya konferentsiya po probleme vibratsionnogo i pul'satsionnogo goreniya. Diskussiya (Discussion: Transactions of the First All-Union Scientific-Technical Conference on Problems of Oscillatory and Pulsating Combustion). Moskva, 1962. 44-46. TAKEN FROM: Referativnyy zhurnal. Mekhanika. Svodnyy tom., no. 12, 1963, 8. Abstract 12 B625.

35*) Trudy. 1-ya Vsesoyuznaya nauchno-tekhnicheskaya konferentsiya po probleme vibratsionnogo i pul'satsionnogo goreniya. Diskussiya (Discussion: Transactions of the First All-Union Scientific-Technical Conference on Problems of Oscillatory and Pulsating Combustion). Moskva, 1962. 94-115. TAKEN FROM: Referativnyy zhurnal. Mekhanika. Svodnyy tom, no. 12, 1963, 98-99. Abstract 12 B626.

INQUIRY ON AVAILABILITY OF TRANSLATIONS

I am interested in availability of translations of the sources indicated below (please enter reference numbers given in the Table of Contents).

____

____

____

Return this form to the local monitor of the OAR-ATD project or mail it directly to:

Head, Science and Technology Section
Aerospace Technology Division
Library of Congress
Washington, D. C. 20540

ATD DISTRIBUTION LIST
WORK ASSIGNMENT 53

ORGANIZATION	No. of Copies
NASA(AFSS-1)	1
NASA(Tech. Lib.)	1
DDC	20
DIA(DD/DIA/SA/GI)	4
CIA(SD)	3
Gen. Ast. Res. Corp.	1
Nat. Sci. Found.	1
DIA	1
RAND	1
SAK/DL-510	2
AMXST-SD-TD	5
CIA(OCR-STAN. DIST.)	6
AFTAC/IG-I)	1
Env. Res. Asc.	1
Tech. Doc.	1
AEDC(AEY)	1
Nat. Bur. Stand.	1
ESD(ESY)	2
ESD(ESTI)	1
ASD(ASF)	1
McGraw-Hill	10
TDBTL (Tech. Lib.)	5
TDBXP	3
AIR UNIVERSITY	1
U.S. Naval S & T Intell. Center	3
AFCRL (CRTEF)	3
AFOSR(SRA)	3
ARL (ARI)	1
OAR(RRY)	1
	3

UNCLASSIFIED

UNCLASSIFIED