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CERTAIN PROBLEMS OF UNSTABLE COMBUSTION IN ROCKET ENGINE CHAMBERS DRIVEN BY LIQUID FUEL

Henryk Krajewski

General Problem.

The problem of unstable combustion in a rocket engine chamber operating in liquid fuel plays a decisive role in phenomena of unstable operation of the entire driving system. The nature of the cause of the combustion process - whether it is stable or unstable, and what type of instability will be - has a principal effect on the thing, on whether the rocket engine functions surely in the given area, or do certain working parameters undergo changes which may affect cause destruction of the driving systems. Actually, the purpose of investigating combustion instability is the description of conditions reducing vibrations to such a degree that it would not negatively affect the work of the driving system. We deal here namely in the relationship and effect of definite parameters.

The problem is not only highly important, but also interesting. There is no wonder that in trade literature, authors devote to it recently much place and attention. But it must be mentioned that although regular international symposiums pertaining to combustion problems are taking place and the published materials are quite voluminous, on the subject of combustion instability in rocket engines, the number of monographs which appeared in recent years can be counted on the fingers. In the Polish language, a few of the publications which appear on this subject, but only in 1963 is the development of only a fragment of the matter.

Characteristic is also the fact that authors of published referendums, articles, and books underline a series of problems which so far have been opened as not sufficiently investigated or not fully explained.

The cause of it is not only the thing that the solving of these problems requires long lasting and costly experiments and tests and development of new methods and measuring means, assuring proper reliability and accuracy, but also the difficulty and complexity of the very problems. Combustion problems include branches of sciences, from which - as the most important - should be mentioned aerodynamics, thermodynamics, and chemistry. Only in the bases of these sciences alone, on the basis of aerothermochemistry (the creator of this science is T. Karman) is possible to explain the kinetics of processes taking place in the combustion chamber of a rocket engine.*

This monograph takes on the purpose of discussing only certain problems of unstable combustion in a rocket engine combustion chamber, namely, the types of instability, their manifestations, causes, and possible results for the drive, stability criteria and conclusions.

First of all, what is considered as "unstable combustion?"**

As unstable combustion is considered durable - without tendency of returning to the output state - and a considerable deviation from normal basic values of parameters accompanying transformation of driving medium components into gaseous combustion products. These deviations can acquire the nature of pulsation (vibrations) lateral and longitudinal, of various sygnal form, or various dissociation, amplitude and frequency at constant or growing average value of these parameters. Speaking about the basic operational parameters of rocket engine operations, we keep in mind the thrust and rapidity and outflow of the factor from the exit nozzle and with respect to processes and combustion conditions - pressure in the chamber and pressure drops, temperature, individual yield of the fuel and oxidizer and combustions. rate of chemical reaction and ignition lag.

The last one of the mentioned parameters τ is especially important.

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*Basic equations of aerothermochemistry were introduced by the author in article "Similarity criteria of combustion chambers of liquid fuel rocket engines - Technika Lotnicza, ed. 11, 1963.

**Crocco and Cheng assumed that combustion takes place normally when the observed vibrations depend only upon phenomena of local nature and decomposes accidentally in various KS places, so that the distrubances appearing in one place has no effect on the operation in sufficiently distant places.

It is the time necessary for heating the mixture from the initial temperature to ignition temperature. Its variable value is connected with the type and mutual magnitudinal relation of driving medium components; the rights of their transformation into combustion products play a very important role in the mechanism of unstable work of the rocket engines; τ has an effect on the possibility of unstable combustion process in the period of changing the working conditions of the engine; that is, during the start, and in the case of an engine with regulated thrust - also during the change in thrust.

Fig. 1 illustrates the ignition lag τ during the combustion process. Fig. 2 represents the relationship of this parameter with temperature τ and the rate of reaction u. Szaulow and Lenner maintain (1961) that authoritative data are lacking so far, data pertaining to the dimensions of lagging time, as well as to its relation with known theses of the combustion theory.

When ignition lagging time will increase to impermissible boundaries, and the yield of the components of the driving medium is extremely great, as a result of accumulating the latter in the combustion chamber (KS), it may, as a result of extreme pressure rise (Fig. 3), come to an explosion of the combustion chamber. That is why the starting belongs to the most dangerous and complicated areas of rocket engine operation.

The basic parameter is the pressure in the combustion chamber. The value of pressure and its change is connected with the value of the other parameters.

The area of instability problems is quite wide, as to enable to exhaust the same within such scanty frames. That is why some authors are engaged in the starting problem only, others in the stability analysis of the "flame front," still others in the area of various types of instabilities - according to classification which is generally uniform, although in literature it is emphasized that the mechanism of origination of irritations of various areas of sensitivity is not sufficiently well investigated. According to adopted nomenclature, it is possible to divide unstable combustion into lower frequency combustion and into high frequency combustion.

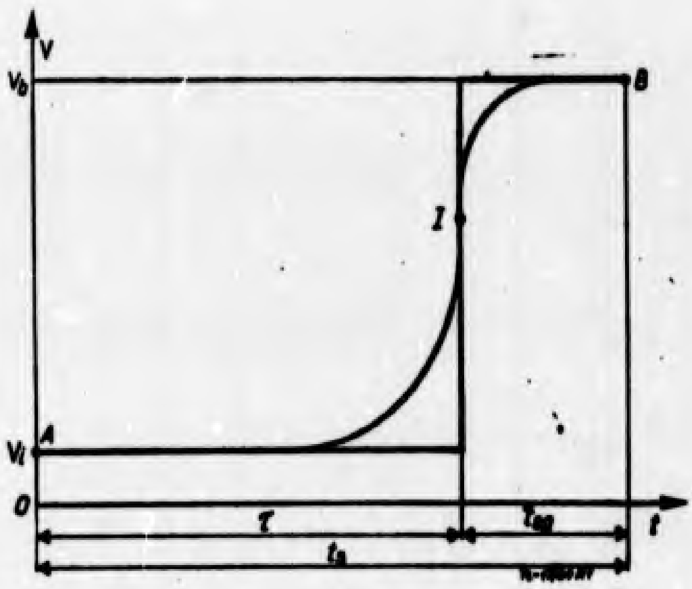

Fig. 1. Change in the volume of active bodies in the cylindrical part of the KS (combustion chamber). τ - lagging time; t_{sg} - time of exposure; t_s - total exposure time.

As unstable combustion:

- of low frequency is considered combustion of vibrations from 30 - 50 to 180 - 220 c (pressure fluctuations with eigen frequency of the combustion process of the driving medium), appearing as a result of the delay between fuel components and oxidizer inflow processes into the combustion chamber and their combustion,

- high frequency is considered vobrational combustion of 600 - 1200 c and generally higher than 1000 c, representing resonance, acoustic vibrations longitudinal of gas, filling up the combustion chamber.

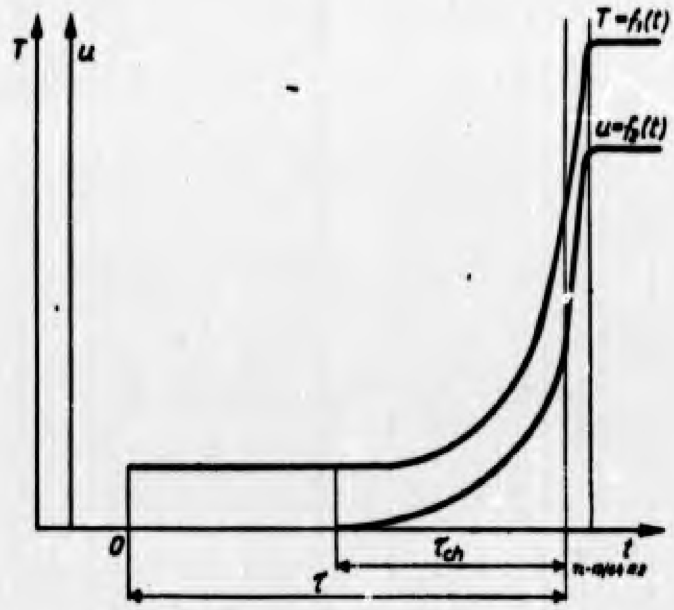

Fig. 2. Temperature diagram T and of rate of reaction u in function t. r - time of ignition delay; τ_{ch} - time from the beginning of chemical reaction to the appearance of the flame.

In addition, there is also detonation combustion (very little recognized) which appears at the moment of engine starting.

It is necessary to warn in advance that the mentioned instability areas of the combustion process never appear in the pure form, but they are ordinarily mutually imposed and are bound with each other.

Frequency and oscillation amplitude of all types - in greater or smaller degree - depend upon:

1) construction and parameters of head and combustion chamber, form of chamber, and the mutual relationship of its geometrical parameters;

2) construction and parameters of the amplification system of driving medium components and auxiliary elements of the driving system;

3) engine performance accuracies and co-activity of all its elements;

4) chemical and physical properties of driving medium components;

5) construction and parameters of flying apparatus in which the driving system is installed and the conditions of its flight; and

6) working conditions of the rocket engine.

Physical picture of low frequency instability.

At the bases of low frequency instability mechanism lies a disrupted, lagging inverse compression system between pressure in the combustion chamber, the yield of driving medium components and the lagging time dependence of ignition upon pressure. The pulsation amplitude reaches up to 50% of average pressure value (fig. 6.) The cause of their appearance (according to agreeable interpretation of soviet and western authors, with the exception of Mebus) is that the fuel and oxidizer transform into combustion gases not as quick as lightning, but after expiration of a certain time, called the conversion time or ignition lagging time τ (fig. 2 and 3.)

It should be added, that according to recent investigations (Zeldovics) the most active for the kinetics of chemical reaction factor is not the ignition temperature, but the combustion temperature of driving medium components (fig. 4.)

It is possible to explain the method of instability creation of low frequency by the diagram representing (in a simplified method) the dependence of a proper volume of combustion products v_2 upon the proper volume of liquid components v_0 in the form of a broken curve, as in fig. 5.

When at the moment t – as result of action of incidental causes – pressure in the combustion chamber will drop to a smaller value than the initial $p_{2\ unit}$, the pressure drop on the injector will rise to

$$\Delta p_1 > \Delta p_{1\,\text{begin}}$$

An increase in pressure drop will cause a rise in singular yield in driving medium components to the combustion chamber

$$G_1 > G_{\text{begin}}$$

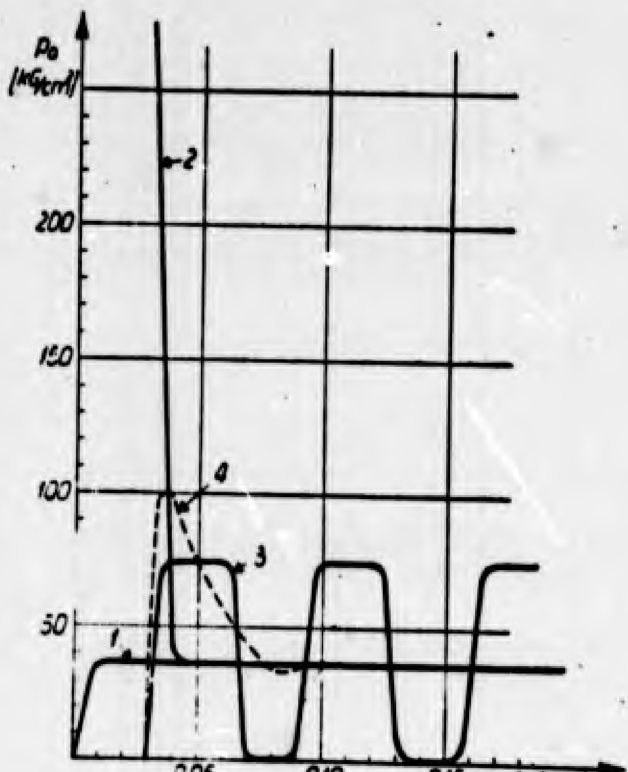

Fig. 3. Pressure change curves in KS at starting; 1–without ignition lag, 2–with ignition lag at rapid (explosive) combustion of accumulated components in KS, 3–each particle ignites at a definite time from the moment of getting into the KS, 4–ignition lag depends upon p_0 and T_0.

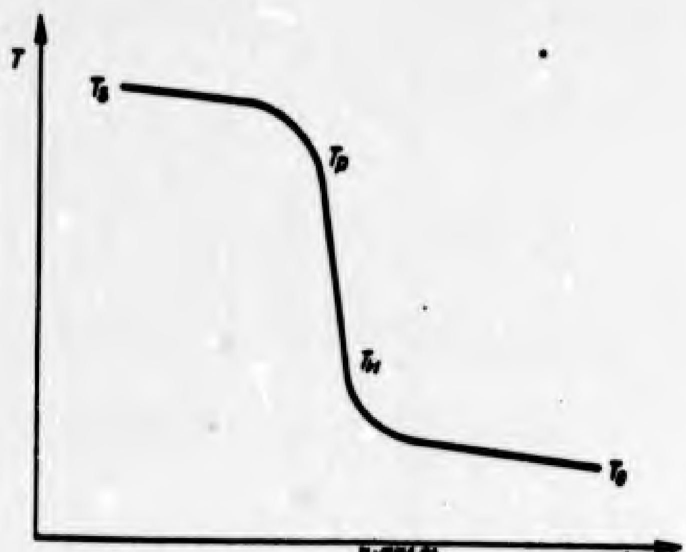

Fig. 4. Nature of temperature decomposition T on the depths of flame front 1 during combustion. T_0 – initial temperature of mixture, T_V – temperature of factor explosion (300–500°C,) T_S – combustion temperature (1000–2000°C.)

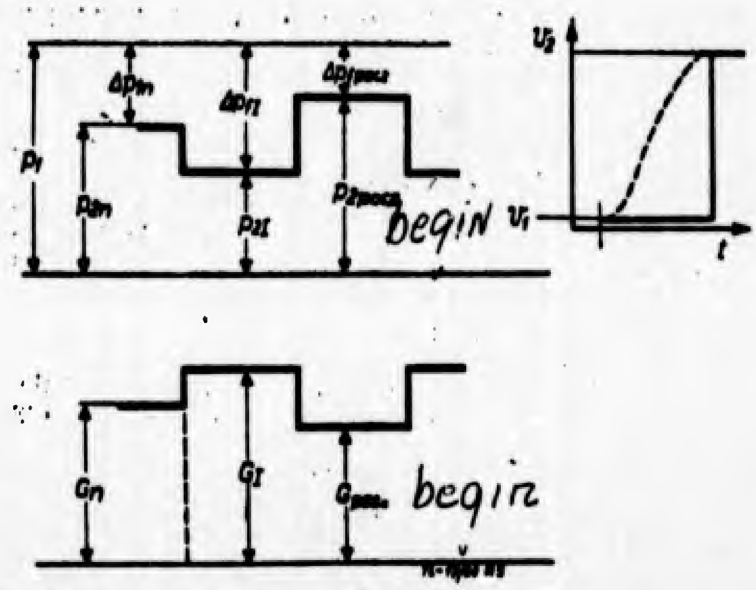

Fig. 5. Schemata of the mechanism of low frequency combustion pulsation origination. p_1-injection pressure, p_2-pressure in KS, Δp-pressure drop on injectors.

Outlay increase cause a pressure rise in the combustion chamber. But this phenomenon will not take place then, but will repeat itself periodically after expiration of time τ, 2τ, 3τ and so on. In certain vibrational conditions vibrations may disappear, and in some they may amplify. Particularly favorable to the origination of vibrations of certain unextinguished thrust regulation system by reduction of yield of driving medium components. Pressure drops on the injectors decrease then and the engine easily falls into the area of unstable operation.

Of course, not only pressures experience vibrations, but also the yield and temperature in the combustion chamber and at the outlet from the injection nozzle. Velocity fluctuations of the stream and pressure in amplification conduits have the very same frequency that p_2 has, but a lower amplitude. The authors bind these phenomena with low pressure in the combustion chamber and small pressure drop on the injectors. The temperature and pressure in various points of the KS agree in phase.

Low frequency vibrations can be of two types:

1) high amplitude vibrations - greater pressure rise within 0.001 sec. (fig. 6,) and then its drop by the interpretation curve as results of interruption in the flow of driving medium.

This pressure drop lasts until as a result of inflow of driving medium components it will rise again. The combustion chamber will be empty for some time because the components do not ignite immediately because of the lag. The time constant of the gradual pressure drop corresponds to the so-called time of stay (of the driving medium component in the combustion chamber,)

2) small amplitude vibrations - if the average pressure in the combustion chamber is increased by increasing the pressure in the amplification system, the vibration frequency will rise, but the amplitude will decrease. There will be no violent pressure drops, but it will become modulated. The form of signals will be sinusoidal (fig. 6b.)

Besides these two cases can take place mixed phenomena (fig. 6c,) in which the amplitude is not constant, and the imposition of several frequencies of accidentally existing frequencies (may take place at $p_2 > 25$ kg/cm^2.)

In the period of starting are often observed vibrations of growing amplitude (fig. 6d.) The vibrations are then extinguished. Their cause is so far unexplained.

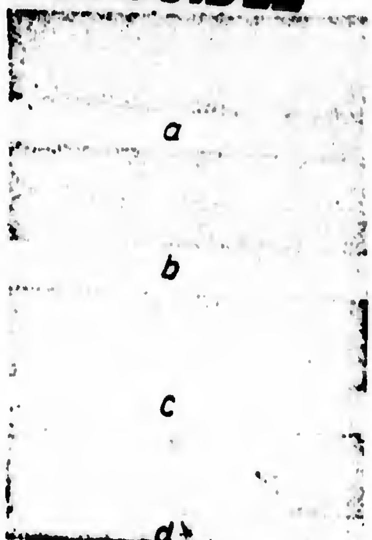

Fig. 6. Oscillograms of pressure vibration signals at unstationary combustion of low frequency.

The first theories, which originated in 1941, which brought the pulsation causes to the time of ignition delay, bound the origination of low frequency instability with the type of driving medium, it means with auto-ignition and not with auto-ignition. An error was the investigation of the phenomenon as unchanged pressure oscillation in time. Later was proven the effect on the phenomenon of unstable combustion of local pressure and temperature changes because the lagging time does depend on them.

Giving a similar picture of low frequency instability mechanism (chugging) Crocco and Cheng call attention to still another type of mechanism - inside chamber instability, constituting self excitation vibrations, regardless of the nature of the amplification system.

It is a relaxation process in the combustion chamber, originated by the reaction of the oscillations of physical parameters on the rate of combustion. Exponential extinction of disturbances with time characterizes the specific time constant - at times the relaxation of the chamber. It is the time in which the disruption decreases by e-times.

All these types of low frequency vibrations may affect simultaneously, mutually amplifying.

Physical picture of high frequency instability

The instability of high frequency is characterized by the presence of longitudinal gas compression waves moving periodically along the combustion chamber from the head to the outlet nozzle and back. The physico-chemical processes taking place in the combustion chamber at the time of lagging develop at velocities, which are affected by pressure and temperature of gases and liquid, their relative velocities along the KS and so on. When the mentioned factors are changed their relative velocities also change, and with them the lagging time.

The oscillations of the mentioned parameters with respect to their average value give a time lagging oscillation of corresponding particle volumes of driving medium. If for example in the definite place of the KS the lagging time rises, it will cause an extension of the process in time and in space, namely a reduction in the rate of combustion.

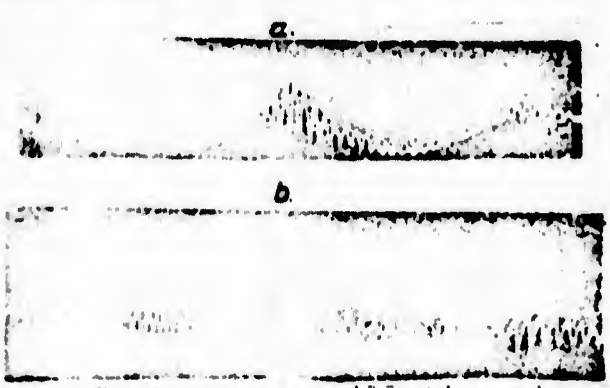

Fig. 7. Oscillograms of pressure oscillation signals during high frequency unstable combustion (amplitude rise up to ± 50%.)

Inversely-the rate of combustion will rise when the lagging time will decrease. As result of this in the KS = combustion chamber may appear periodic longitudinal pressure pulses (compression waves) from the head to the outlet nozzle (DW,) reflection of same and return movement. If these pulses attain great value then conditions of independent amplification are created for the amplification of eigen oscillations and longitudinal waves. The work of the KS becomes in this case unstable. The period of the cycle of these oscillations is approximately equal to the time of lagging and time of spreading the pulse of pressure from the head to DW and back. It is necessary to mention, that temperature fluctuations in the KS and at the output of DW are not in phase.

Frequency of longitudinal high frequency oscillations is inversely proportional to the length of KS.

It should be underlined, that pressure oscillations in the KS have different effects on the yield of unit components of the driving medium, that is fuel and oxidizer, as result of which as result of change in their load relation will be changed the lagging time, rate of combustion, temperature and pressure of gases, which again in a very real way affects the disruption of static engine operation.

The frequency of the discussed oscillations is very high, of the order of somic wave oscillations. In spite of the low amplitude they are very dangerous. High frequency instability does usually not appear in "pure" form, but in form of imposition of high frequency over low frequency (fig. 7a and b,) whereby the instability of high frequency appears mainly at maximum pressure at low frequency, which means, that increase in pressure causes fortification of this phenomenon.

In contrast to low frequency oscillations where such a low amplitude may appear, that it may be disregarded, in case of high frequency instability occur amplitudes reaching up to ± 50 ÷ ± 100% (fig. 8a-c;) the form of the signal is also very various: from the pure sinusoid to stream pressure jumps. This latter type of instability is - a clear fact - the most dangerous. Observation results (e.g. by Summerfield, Siemionov, Szaulow and others) agreeably confirm that the time of circulation of pressure wave is commensurable with the period of oscillations. In the vicinity of the arrow formed by the standing wave - as result of wave interference from head to DW and the return wave from DW to the head - is observed maximum deviation in rate of combustion, thus the maximum tendency to instability.

Results of combustion instability

It was mentioned several times that combustion oscillations may be dangerous. It is necessary to briefly explain in what the danger lies. It may have a different nature:

Fig. 8. Pressure oscillation signal oscillograms during unstable high frequency combustion (amplitude rise to ± 100%.)

a) increase in pressure amplitudes to high values, having the nature of sudden jumps, threatens destruction of the combustion chamber of the engine and of the flying apparatus and creates danger for people;

b) at pressure pulsations in the KS, yielding of warmth to the walls may be 1.5 - 2.5 times greater than during static work, which may cause their overheating and burning;

c) pulsations of rate of combustion, temperature and individual heat separation and decomposition in rate of flow through of the factor may cause local overheatings and burning of KS walls:

d) combustion oscillations, causing thrust pulsation, interfere with the work of the drive reducing attainments of the flying apparatus;

e) thrust pulsations, in case of resonance with eigen frequency of the entire construction may cause disruptions in the fastenings of amplification conduits and of the entire construction.

continuation in next edition