THE PROBLEM OF COMBUSTION INSTABILITY IN LIQUID ROCKET ENGINES

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INTRODUCTION

The issue of combustion instability was first discovered in the 1930s for solid and liquid rocket engines. However, the solution of the problem did not see significant development until the late 1940s, when the phenomenon of instability became more complex during the development of large intercontinental ballistic carriers, necessitating a deeper systematic approach to studying this phenomenon. One of the first widely known cases of studying combustion instability was the F-1 engine by Rocketdyne. In the 1960s, during its development, engineers spent around 7 years searching not only for methods to prevent this phenomenon but also for the reasons behind its occurrence [1, 9, 11].

Despite the significant amount of work conducted by engineers in the past to identify the main causes and characteristics of instability, there is still no clear correlation between design features and the occurrence of such phenomena in modern rocket engines. The extreme operating conditions of materials and structural elements determine the uniqueness of each design, as well as the set of factors that directly affect the stability of the combustion process. This paper partially reviews historically known cases of combustion instability and examines the main classification of known types of instability that occur in rocket engines.

The results of the development of the new low-thrust engine, manufactured with additive technologies are described in this paper as well as the problem of low-frequence instability that occurred during fire testing. The results of the work carried out could be further developed by considering the issue of combustion instability in modern rocket engines.

OBJECTIVE AND TASKS

The aim of this work is to assess the state of the issue of combustion instability in liquid rocket engines with a view to further development in the context of modern designs. To achieve this, it is necessary to:

– Conduct a literature review on historical cases of combustion instability in rocket engines;

– Examine the existing classification of types of instability and possible methods for preventing them.

To explore the features of combustion instability in liquid rocket engines, an analysis of the existing literature on the subject and a description of its occurrence in well-known designs have been conducted.

BRIEF OVERVIEW OF COMBUSTION INSTABILITY IN THE KNOWN ENGINES

When considering the problem of combustion instability, it is impossible to isolate factors that pertain to only one type of engine. This phenomenon occurs in both solid rocket engines and liquid rocket engines. To better understand the scope and duration of the development of methods for preventing this issue and theoretical structuring, Figure 1 presents a chronology of the emergence of the combustion instability problem.

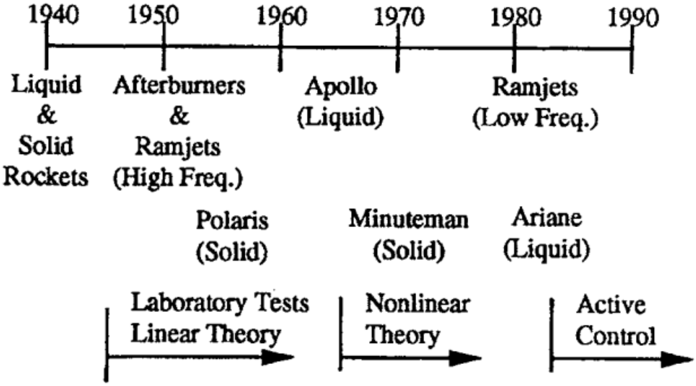


Figure 1 – The chronology of the emergence of the combustion instability phenomenon and the development of the corresponding theory [1]

A list of engines with known cases of combustion instability, as well as the work conducted to identify the causes and design methods to combat this phenomenon, is provided. The list of engines is presented in Table 1.

Table 1 – List of engines with known occurrences of combustion instability

Engine model	Propellants	Thrust, kN	Designation
F-1 [1]	LOX + RP-1	7740.5	First stage rocket engine of the Saturn V rocket
RD-0110 [7]	LOX + Kerosene	298	Third stage of the Soyuz carrier rocket
H-1 [3]	LOX + RP-1	900	The main engines of the first stages of the Saturn-1 and Saturn-1B carrier rockets
RD-216 (8Д514) [2]	N_2O_4 + UDMH	1728	The main engine of the R-14 rocket. Later, the main engine of the first stage of the Kosmos-3M launch vehicle
RD-217 (8Д515) [2]	N_2O_4 + UDMH	865	The main engine of the first stage of the R-16 rocket
TR-201 [1, 8]	N_2O_4 + Aerozine 50	41.9	The upper stage engine of the Delta launch vehicle (known as Delta-P)
Lunar module descent engine (VTR-10) [1]	N_2O_4 + Aerozine 50	47	The engine developed for manned carrier operation and lunar surface landing
XLR-132 [4]	N_2O_4 + MMH	16.7	The engine developed for the upper stage booster blocks, lunar, and Martian mission spacecraft
AJ10-137 [11]	N_2O_4 + Aerozine 50	91	It was used for launching into lunar orbit and descent from it during the lunar program
Lunar Module Ascent Engine [8]	N_2O_4 + Aerozine 50	16	For ascending from the surface of the Moon during the lunar program.
Space Shuttle Primary RCS Thruster [1]	N_2O_4 + MMH	4	For controlling thrust vector during liftoff, maneuvers, and descent to Earth
AJ10-190 [11]	N_2O_4 + MMH	26.7	For operation in orbit and ascent from it
YF-20 [6, 8]	N_2O_4 + UDMH	750.2	The main engine of the first stage of the Long March 2-4 vehicle
YF-1 [5, 8]	N_2O_4 + UDMH	303.6	The main engine of the first stage of the Long March 1 vehicle

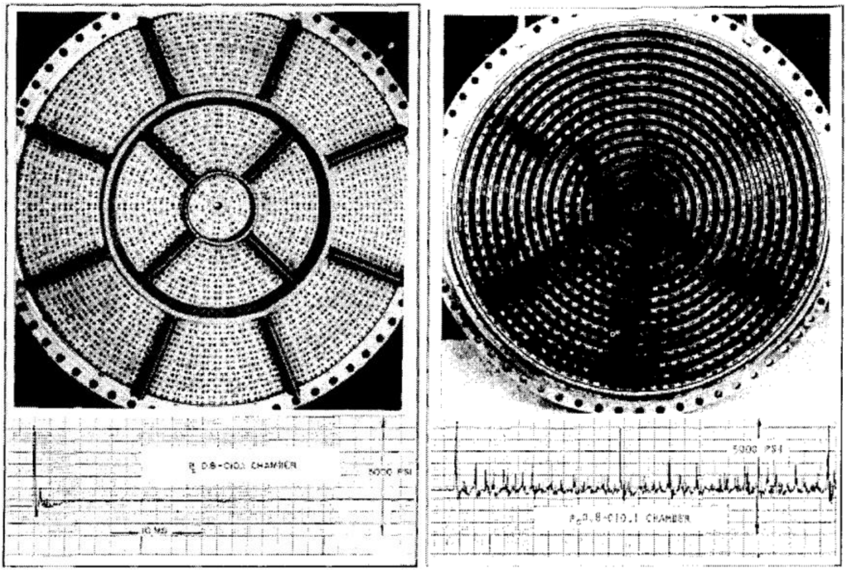
As can be seen from Table 1, the combustion instability problem is quite widespread and encountered in the development of engines with different characteristics and fuel components. Let's consider some features related to the operation of the listed engines.

F-1 Engine [1]. During the development of this engine, strict requirements were imposed, mainly related to the mission of sending humans into space. However, combustion instability issues, extensively described in NASA technical reports, mostly allow identifying the following main reasons for initiating combustion instability:

– The influence of film cooling, which creates conditions for pulsations by separating part of the flow from the wall boundary layer and creating conditions for detonation-like combustion.

– Atomization of fuel components in the critical mode of components, ultimately resulting in high velocities of burning and causing pressure oscillations.

These problems were addressed by optimizing the film cooling thickness and by varying the mixing head configurations. The primary method of addressing combustion instability was dividing the combustion zone into individual sectors using special baffles, ultimately leading to stabilization of the combustion process (see Figure 2).



a) with baffles b) without baffles

Figure 2 - Mixing head of the F-1 engine chamber and pressure oscillogram in the chamber [1]

RD-0110 Engine Chamber [7]. During the development stage of the engine chamber, a significant number of mixing head layout schemes were considered to ensure high combustion stability. During the research process, theories regarding "enlarging" of the combustion zone to increase the release length of combustion kinetic energy were tested, which, when shortened, led to pulsations. This method is feasible when using jet injectors as part of the mixing head. The applied methods resulted in several combinations of injectors configurations in the engine chamber mixing head. However, increasing the length of the "combustion zone" did not yield the desired result, and the obtained results formed the basis for finding such a variant of the layout of the engine chamber mixing head that would provide reliable stability of the combustion process across the entire operating range. Eventually, such a variant was found and implemented in the engine chamber design.

However, in rare cases during fire tests at the customer's facilities, instability of the combustion process was observed in one out of 60–80 cases, leading to significant damage to the engine chamber and part of the test equipment. Analyzed data from such tests revealed that, for reasons that cannot be objectively justified, the occurrence of instability could be explained by the individual interaction of the test equipment with the engine chamber design. Although no stability issues arose in the flight configuration, design measures were taken to ensure stability of the working process for manufactured structures. Regarding unpredicted possibility of the emergence of the combustion instability the search for means for studying the phenomenon was needed. Thus, engineers came up with a set of equipment which ensures initialization of combustion instability process, is able to sense it and stop it before the oscillations were able to damage not only a specimen of combustion chamber, but also test stand equipment. After extensive research was carried out, the solution to the problem of combustion instability in RD-0110 engine was found. Sets of acoustic fins were manufactured to ensure stable operation without the occurrence of combustion instability. The fins were made of felt, so after the engine was launched, they burned out and had no further impact on the chamber's steady-state operation. The proposed design solution was successfully implemented in the already produced RD-0110 engines.

Lunar Module Descent Engine (LMDE) [8]. The engine was subjected to strict requirements due to the necessity of fulfilling the mission - landing two astronauts on the surface of the moon. Naturally, the occurrence of combustion instability was totally unacceptable for the LMDE engine. To accomplish the mission, the engine needed to have the capability of deep throttling, which ultimately led to the use of a special pintle injector system (see Figure 3).

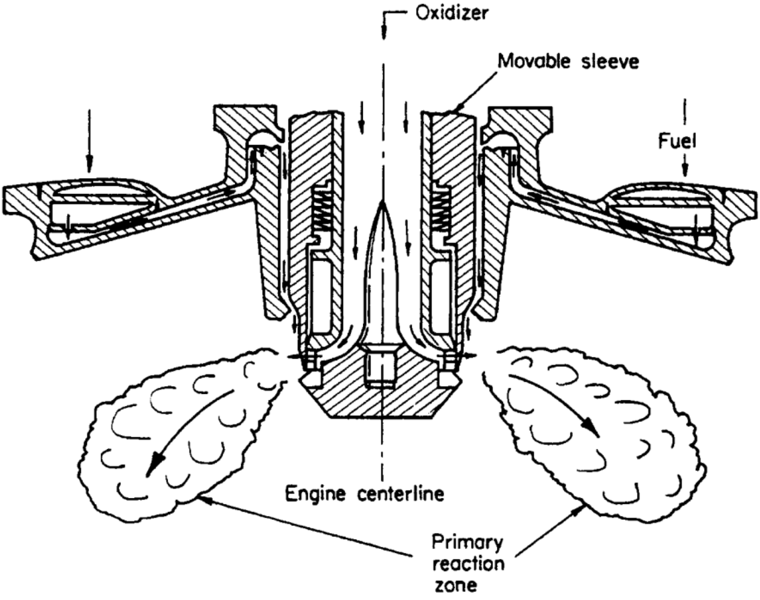


Figure 3 - Injector of the Lunar Module Descent Engine (LMDE) [1]

During the testing of the engine chamber and artificial initiation of instability, the development of the process did not occur, confirming the success of the chosen design solutions. One explanation for this effect likely involves the relative distribution of acoustic pressure and combustion energy release. Fuel components are distributed along the annular region between the chamber wall and the injector, which has a positive effect on the stability of the process. However, during further extensive testing programs, data were obtained indicating the occurrence of transient pressure pulsations during rapid throttling or operation of the chamber at maximum thrust with excess fuel. Overall, the developed engine chamber design is considered successful, fully ensuring process stability under the specified operating conditions.

Thus, it is evident that the problem of combustion instability arises in various designs of liquid rocket engines during their development and typically requires a significant amount of work to identify the cause of the problem and ways to overcome it.

When working with liquid rocket engines, it is important to understand the classification of types of combustion instability for effective implementation of means to overcome the occurrence of this phenomenon in the designs of rocket engines under development. Let's consider the proposed classification.

CLASSIFICATION OF COMBUSTION INSTABILITY TYPES IN LIQUID ROCKET ENGINES

Usually, the following types of combustion instability are distinguished as follows [1, 9–12]:

– *Low-frequency* oscillations, which are the simplest examples of combustion instability, where pressure oscillation amplitudes at all points within the combustion chamber volume are equal and typically range from 20 to 200 Hz.

– *High-frequency* combustion instability, which is the most destructive type of instability. It is also known as acoustic instability or resonant combustion, typically occurring at frequencies of 400 Hz and above.

– Instability at *intermediate (transient)* frequencies, encompassing all types of instability not classified into the first two categories, with oscillation frequencies ranging from 100 to 400 Hz.

CAUSES OF INSTABILITY IN THE COMBUSTION PROCESS

Low-frequency oscillations are often caused by:

– Interaction of the combustion process with the fuel injection process through the mixing head;

– Interaction of the combustion process with any of the rocket engine systems.

High-frequency combustion instability is typically caused by the combustion process itself, or more precisely by effects such as:

– Delayed ignition;

– Time for physical and chemical preparatory processes;

– Detonation;

– Change in the rate of chemical reactions due to pressure and temperature fluctuations;

– Disruption and mixing of jets, films, and droplets under the influence of gas pulsations.

Instability at intermediate frequencies is usually associated with increasing coupling of combustion noise at any frequency, with the amplitude of oscillations gradually increasing. Such combustion instability is often characteristic of rocket engines with adjustable thrust, as among the variables, there is usually a combination that contributes to its occurrence.

METHODS FOR PREVENTION OF COMBUSTION INSTABILITY

To suppress low-frequency oscillations, methods such as the following are often used:

– Increasing the pressure drop at the injectors;

– Increasing the volume of the combustion chamber.

To suppress high-frequency oscillations, methods such as the following are often used:

– Search for the optimal design of the mixing head and its parameters;

– Use of damping devices.

Among the types of instability mentioned above, **high-frequency instability is the most destructive**. There are longitudinal (axial) and transverse (radial, tangential, and combined) types of high-frequency oscillations (see Fig. 4).

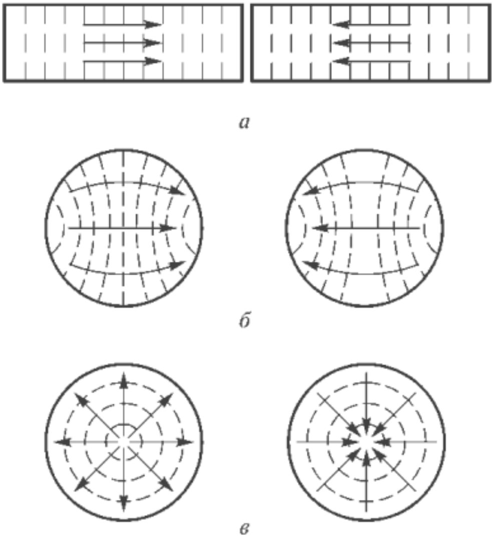


Figure 4 - Types of high-frequency oscillations in rocket engine combustion chambers [11]:

а – longitudinal; б – tangential; в – radial; - - - - – equal pressure lines.

High-frequency longitudinal oscillations occur along the axial direction of the combustion chamber. During these oscillations, gas parameters in the chamber change along its axis, while across the chamber's cross-sections perpendicular to the axis, gas parameters have the same values.

In transverse oscillations, gas parameters change across the chamber's cross-section, perpendicular to its axis, while remaining unchanged parallel to the axis. *Transverse* modes of high-frequency oscillations are usually the most dangerous type of high-frequency instability.

Combustion instability is also divided into linear and nonlinear types:

– Linear instability does not require initial excitation and can start from combustion process noise. In rocket engines prone to such instability, oscillations may appear immediately upon reaching nominal mode.

– Nonlinear instability is always caused by finite excitations. Such excitations in the combustion chamber manifest as "bursts" and "spikes." "Spikes" refer to pressure surges in the chamber during fuel ignition. "Bursts" refer to sudden pressure surges that appear during engine operation at nominal mode. These excitations can be inherent to the working process or induced externally.

ISSUES WITH COMBUSTION INSTABILITY IN THE DEVELOPMENT OF A PROSPECTIVE 200 N THRUST ENGINE

The authors have conducted the development of a prospective small-thrust liquid rocket engine (SLRE) at 200 N, manufactured using Laser Powder Bed Fusion (L-PBF) additive technology. The fuel components used are a storable combination of N2O4 + UDMH, with a pressure-fed engine cycle. The mixing head is based on centrifugal injectors, and mixing and combustion occur on the chamber wall.

The chosen concept of maximum L-PBF technology utilization for engine chamber manufacturing mandated additional refinement of the mixture formation system elements due to insufficient statistical information. During development, the authors encountered the need for substantial research in terms of the quality of centrifugal injector spray—determining a combination of design parameters that would ensure the required uniformity of liquid distribution in the spray cone at the specified pressure drop. After confirming the selection of the complex of constructive parameters of the mixture system, work was done to find a rational variant ensuring high dynamic characteristics of the engine chamber.

The next stage, aiming to confirm the effectiveness of the embedded technical solutions, involved a series of ground firing tests of experimental chamber specimens. These samples were simplified versions to check the operability of the mixture system. The results of the firing tests showed high performance, confirming the effectiveness of the prospective engine chamber organization.

Further optimization of the design was aimed at integrating the mixture system with the chamber body. During the firing tests, *the authors encountered the problem of low-frequency combustion instability for the developed design*. The frequency of pressure oscillations was approximately **1 Hz**, resulting in significant pressure oscillation amplitudes in the engine chamber and decrease in process efficiency. Therefore, further development required determining the cause of pressure oscillations and methods to prevent this phenomenon.

The influence of raw surface roughness of the chamber wall, typical for the L-PBF additive method, was identified as the main contributor to the low-frequency oscillation. Subsequent polishing of the wall surface and slight modification of its design resulted in the combustion process becoming stable, with the operating efficiency increasing to its nominal level, and the pressure oscillation amplitude reaching a minimum value acceptable during engine operation.

RESULTS

A review of combustion instability problem in liquid rocket engines described in available literature has been conducted. It has been shown that the problem of unstable operation of rocket engines is a complex multi-component phenomenon, typically characterized by individual features specific to each particular design under development.

Based on the conducted review of design problems in known liquid rocket engines, a classification of types of combustion instability, the main reasons for their occurrence, as well as methods of preventing such phenomena, have been considered.

The work on the development of the design of a prospective low-thrust engine chamber, manufactured using L-PBF additive technology, has yielded the following conclusions:

– The increased roughness characteristic of L-PBF technology, combined with the chosen mixture system on the chamber wall, can induce low-frequency pressure oscillations in the engine chamber.

– The possibility of applying design means to overcome and prevent low-frequency oscillations in the design of the low-thrust engine has been demonstrated.

– The possibility of obtaining an engine chamber design with high performance characteristics, manufactured using L-PBF technology, has been confirmed.

CONCLUSIONS

The work conducted can serve as a basis for further research on the peculiarities of combustion instability in modern liquid rocket engines manufactured using additive technologies. The obtained results demonstrate significant potential of the technology in designing prospective low-thrust engines and provide a basis for developing engineering recommendations for obtaining highly efficient designs of such engines.

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