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Olexiy NIKOLAYEV, Inna BASHLIY

Institute of Technical mechanics NASU and SSAU, Dnipro, Ukraine

DEVELOPMENT AND TESTING OF THE SOLID FUEL POWER PLANT AXISYMMETRIC MODEL APPLIED TO REGIMES OF COMBUSTION CHAMBER DYNAMIC INSTABILITY

Innovative use of energy resources in deep space planets is a technology that allows a significant increase in space exploration based on the design of rocket power plants, particularly for lunar landing modules using (Lunar Regolith) propellants. Simultaneously, for using such local propellants, effects were found based on the fire test of the developed physical model of the landing module power plant. These effects are characterized by combustion product vortices, thrust oscillations, incomplete combustion or extinction during propellant combustion, as well as the possible development of unstable dynamic processes during combustion product flow in the chamber of a solid-propellant rocket power plant. Unacceptable pressure rise and a sharp increase in the local temperature of combustion products can lead to the strength failure and destruction of the combustion chamber structure of rocket power plants, and transition to a critical operation mode of the rocket power plant. Based on the theoretical determination of the non-stationary process parameters in the test propellant combustion chamber during the combustion product flow, the possibility of implementing this type of working process instability (self-oscillations) in a power plant is shown. The thermodynamic characteristics of a power plant using such a metallized propellant have been numerically determined, and a preliminary analysis of the experimental and calculated acoustic oscillation parameters (thrust, dynamic pressure components, and axial velocity) was performed. The main possible directions of modern research on working process instability in a power plant with propellant obtained from lunar regolith have been determined. The study aims to identify the mechanism of pressure oscillation development in the combustion chamber, analyze and model phenomena associated with propellant ignition (including ignition delay), combustion, and heat transfer, analyze resonant damping in a power plant, develop methods for optimizing the chamber design to reduce the level of pressure oscillation amplitudes, and study the role of aluminum droplets combustion in aluminized propellant in the realization of power plant working process instability.

Keywords: *solid propellant power plant; combustion products vortices; fire test; thrust oscillations; working process instability; dynamic pressure components; acoustic oscillations.*

Introduction

The exploration of near space, which is being produced this year (January - February 2025), is associated with the Blue Ghost Lunar Lander lunar landing mission of Firefly Aerospace on the SpaceX Falcon 9 launch vehicle, and provides further steps in the development of new space technologies. Samuel S. Schreiner et al. [1] provided thermodynamic calculations and proposed burning metals and their compounds mined on the Moon in an oxygen environment in a solid-propellant rocket power plant. They concluded that this Lunar Regolith propellant concept is quite attractive, but significant gaps remain in understanding how these metals will be technologically extracted from the lunar regolith and integrated into the design of the power plant. Meyer [2] compared different technologies for obtaining rocket propellant and considered solid-propellant power plants based on Al/O2 and Al/H2O2 and obtained similar conclusions. These experiments demonstrated the achieved productivity level of the obtained propellant, for oscillation at the level of 50% of the theoretical value. However, several problems were identified in the implementation of the concept of this propellant combustion in the power plant - poor mixing and incomplete combustion.

The main aim of the article is to assess the fundamental possibilities in the design of rocket power plants for lunar rocket landing modules with using ISRU (Lunar Regolith) propellants in terms of problems characterized by incomplete combustion, as well as the possible development of unstable dynamic processes during the flow of combustion products in the chamber of a solid-propellant rocket power plant.

Thermodynamic properties of solid propellant combustion products (Lunar Regolith) in the studied physical model of a test rocket power plant

Thermodynamic properties of solid propellants were investigated in [1, 3 – 4]. In [1], a set of lunar regolith models is presented, which can be used for a wide range of applications. These data correspond to regression models for a number of regolith properties:

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composition, density, specific heat capacity, thermal conductivity, optical absorption length and latent heat of fusion. The thermodynamic properties of the studied physical model of test rocket power plant solid propellant are calculated based on data on the elements composition (in particular, metals Al, Mg) of lunar regolith as propellant. These elements can be used in the studied propellant after the extraction of the necessary components from the soil. The thermodynamic properties of the test rocket power plant solid propellant combustion products are calculated using [5].

Development of the solid propellant power plant axisymmetric model applied to the regimes of combustion chamber dynamic instability

The analysis of the fundamental possibilities of designing rocket power plants for Moon landing modules based on the use of metallized propellant and the study of their combustion chambers dynamic instability was carried out for rocket chamber axisymmetric physical model. The studied rocket power plant has a propellant charge with a ratio of the geometric parameters of its chamber L/dr =6.04 [6]. As the studied propellant, a mixed rocket solid propellant was chosen due to its manufacturability, relative cheapness and relative operation safety (according to a number of physical properties close to the propellant, supposed to be produced from lunar regolith). In addition, in order to perform the research task, for choosing the parameters of the charge based on [4], combustion modes with incomplete combustion and with the possible development of unstable dynamic processes during the flow of combustion products in the chamber were chosen.

To implement such an operating capability of the installation and in the further verification of the numerical method for calculating the internal ballistic combustion parameters, a simplified propellant charge design was chosen mainly from the condition of obtaining the combustion products pressure in the chamber (during the power plant start-up) ~ 40 bar in the chamber and a burning time of at least 1 s. Some of its main operating and geometric parameters are given in Table 1.

The initiation of propellant composition combustion was carried out using an electric match. To measure the power plant internal ballistic parameters, a pressure transducer was used to measure the pressure in the combustion chamber and a strain gauge to measure the thrust.

A simplified diagram of the charge obtained as a result of the design with a schematic representation of the physicochemical processes in the solid propellant combustion chamber and their localization in the working space of the chamber (shown in Figure 1).

The above physical model of the chamber was investigated experimentally quite thoroughly [6]. As previously planned, during the power plant tests, combustion modes with unstable dynamic processes arose. In particular, after entering the power plant main operating mode, the relative experimental amplitudes (relative to the static thrust value in the set mode) thrust $\bar{R}_{exp}$ of the studied chamber were 1.33, and the estimated values of the amplitudes of the pressure oscillations in the operating mode dP= 49.69 bar.

Table 1

Studied combustion chamber operating and geometric parameters

Parameter name, dimension	Marking	Value
Gas pressure in the chamber, bar	$p_{вх}$	37.3
Outer diameter of the combustion chamber cylindrical part, мм	Dr	41.0
Gas temperature in the chamber, K	Tк	2010.0
Speed of sound in gas, м/s	C	1009.16
Gas density in the chamber, kg/м^3	ρ	8.37
Inner diameter of the channel, мм	dr	24.0
Charge length, мм	L	145.0
Critical diameter, мм	dkr	8.0

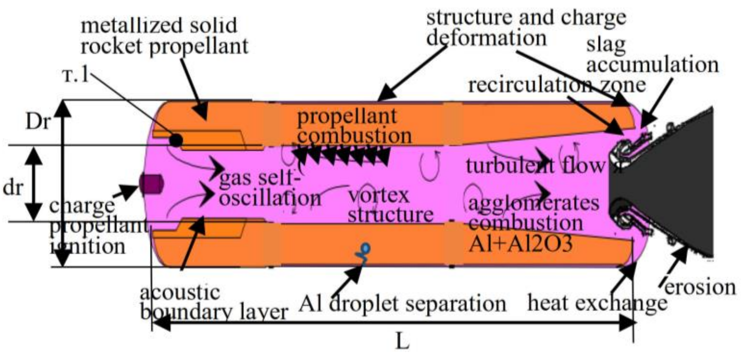

Fig.1. A simplified solid propellant combustion chamber diagram

In particular, the combustion products flow instability in the chamber was realized during the tests in the studied chamber sample and was explained in work [4] by the so-called "blowing effect" detected on some charges, an unsteady process with an increase in the burning rate and with an increase in the combustion products flow rate along the combustion surface. This effect is also theoretically close to the previously described phenomenon, for the propellant combustion extinguished at a certain critical velocity of combustion products flow through the solid propellant charge channel. After the loss of propellant combustion stability in the power plant combustion chamber, the propellant charge is extinguished, but after some time it is re-ignited from hot combustion products. Then, extinction and re-ignition occur again, etc. The so-called "sneezing" mode of the rocket power plant occurs. After this process, the charge either continues to burn without losing stability or completely goes out. At the same time, according to later theoretical and experimental studies [7 – 10], it has been shown that the solid propellant power plants instability can be caused by reverse flows of gaseous combustion products during their gradual movement in the chamber. The mechanism of power plant stability loss is determined not only by the influence of pressure oscillations on the propellant components combustion rate, but also by the acoustic pressure dynamics waves in the combustion chamber [3]. Reverse flows of gaseous combustion products directly affect the dynamics of acoustic intra-chamber processes in the power plants chambers [7].

Formulation of the problem

In the conducted study, an approach to mathematical modeling of gas flow in the power plant chamber was applied using the finite volume method (FVM) and the large eddy simulation methodology (LES) in the CAE system [11, 12]. This approach is presented in [10]. In the conducted numerical modeling, in order to simplify the mathematical description and subsequent analysis of the results, the equations of combustion process chemical kinetics and its effect on heat release were not taken into account. They are necessary to obtain additional characteristics of the combustion products flow and further detail the nature of the internal flow in the chamber. To obtain a more stable solution, the non-stationary problem in the variables velocity - pressure is solved using the Artificial Compressibility method in an implicit scheme and 1st order time discretization. The total simulation time of the unsteady process of the flow of combustion products through the chamber channel (after the time interval for the "power plant start-up" and the "transition" of the studied dynamic system "combustion chamber – combustion products" in the self-oscillating mode) was about 0.5 s, which was sufficient to obtain satisfactory results when performing a numerical analysis of the parameters of the steady-state self-oscillating mode, as well as an analysis of the oscillation frequency spectrum using the fast Fourier transform of the studied dynamic process. In the dynamics numerical study of the power plant test combustion chamber, the results of the studies obtained on the basis of data from two grid models were analyzed, which correspond to the flow of combustion products at the "initial" form of chamber charge burnout – 5% and "after entering the mode" at the moment of calculation time t=0.01 s (1924 grid cells) and the form of the charge at the "final" (approximately 95%) degree of propellant burnout in the chamber at t=1.1 s (2840 grid cells). In this study of the intra-chamber processes dynamics in the test chamber, the following calculation case was considered. It corresponded to the time event (time of steady self-oscillating mode of gas flow (after the transient process power plant "start-up") was implemented (with the "initial" and "final" forms of charge burnout)).

Numerical study of the gaseous combustion products flow process in the power plant chamber

Working process oscillations in the chamber are caused by reverse flows of gaseous combustion products during their gradual movement in the chamber. Fig. 2 shows the calculated time dependences of the dynamic pressure components P_{din} in the studied chamber (in point 1 see Fig. 1) at the beginning of combustion (Fig. 2, a)) and at 95% propellant burnout degree in the chamber (Fig. 2, b)) and the time dependences of the experimental values of relative thrust $\bar{R}_{exp}$ (see Fig. 2, c)) obtained for the studied chamber. For this case, the dynamic pressure component is characterized, as in the experiment (23 Hz, 62 Hz are recorded for the relative thrust experimental values of the $\bar{R}_{exp}$ in Fig. 2, c)) by low-frequency oscillations of 71 Hz both at the beginning of combustion and at 95% propellant burnout degree in the chamber (see Fig. 2, a), Fig. 2, b) 71 Hz is recorded for the calculated values of the dynamic pressure components P_{din} in the chamber).

In addition, at 95% propellant burnout degree in the chamber of up to, 10 Hz is recorded for the calculated dynamic pressure component P_{din} (see Fig. 2, b)). It should be noted that higher oscillation frequencies (above 100 Hz) are also recorded for the calculated dynamic pressure components in the chamber under study (see Fig. 2, a, Fig. 2, b).

Low-frequency oscillations (70 Hz) were recorded for modeling the flow of combustion products. For the dynamic pressure component, vortices are observed that form from the critical cross section towards the cylindrical part of the chamber.

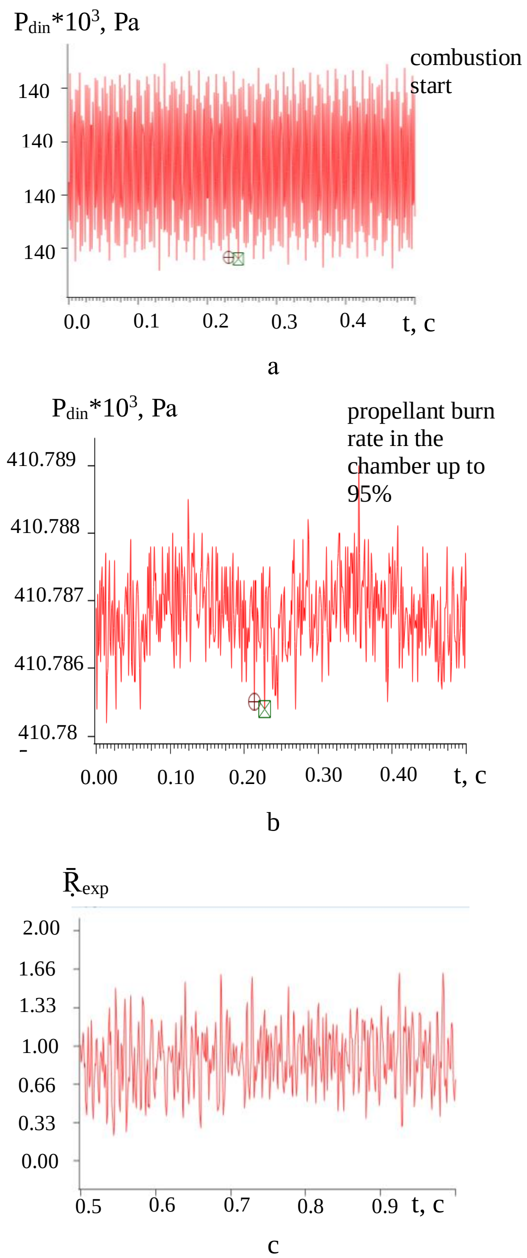

Fig. 2. Calculated and experimental time dependences of results obtained for the studied chamber:
a – dynamic pressure components P_{din} at the beginning of combustion,
b – dynamic pressure components P_{din} at 95% propellant burnout degree in the chamber,
c – experimental values of relative thrust $\bar{R}_{exp}$.

Fig. 3 shows the calculated pressure dynamic components P_{din} in the studied chamber with the "initial" charge burnout form with a non-stationary combustion products flow in the studied chamber for a steady self-oscillating mode of the gas flow with a harmonic sinusoidal disturbance for a dominant oscillation frequency of 70 Hz (as the base frequency of the dynamic system natural oscillations, in Fig. 2). This calculation was carried out in order to analyze the possibility of an earlier transition of the studied dynamic system to the limit cycle and to determine the level of influence of the dynamic system disturbance with this forced oscillations frequency on the amplitudes magnitude of the pressure oscillations in the chamber and the thrust of the power plant.

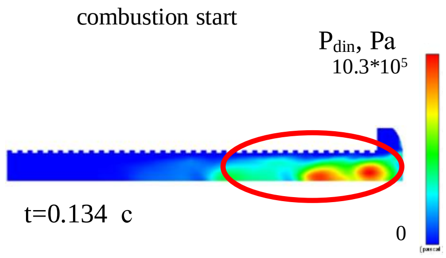

Fig. 3. Dynamic pressure components P_{din} diagram

As follows from Fig. 3 maximum dynamic pressure components P_{din} (numerically determined as steady-state dynamic components of the forced pressure after the vortices collapse during the combustion products flow along the chamber) were 11 bar (amplitude of pressure oscillations in the chamber); this value corresponds to the amplitude of self-oscillations of relative thrust $\bar{R}$ is equal to 0.3 (as a result of converting the numerical value of the pressure dynamic component in the chamber into thrust oscillations), which does not exceed the experimental amplitude of relative thrust oscillations $\bar{R}_{exp}$ in the chamber is equal to 0.66. It should be noted that the calculations were carried out only taking into account the combustion products turbulent flow along the chamber (without taking into account the influence of oscillations on non-stationary chemical processes occurring during propellant combustion).

Application perspectives

Based on the analysis of the data presented above, it is possible to make conclusions about the main directions of modern research into the working process instability in a power plant with solid propellant from lunar regolith. They can be as follows: mechanisms identification for the development of pressure oscillations in the combustion chamber, analysis and modeling of phenomena associated with propellant ignition (including ignition delay), combustion, heat transfer; analysis of resonant damping in a power plant; development of methods for design optimizing of the power plant chamber in order to reduce the level of pressure oscillation amplitudes; study of the burning aluminum droplets impact factor in aluminized propellant for the internal instability of the power plant.

Conclusions

Based on the obtained theoretical and experimental results, the following conclusions were made:

1. A numerical determination of the test sample of rocket propellant thermodynamic characteristics was carried out. These characteristics are close to agglomerates that can be obtained from lunar regolith in terms of a number of chemical and physical properties.

2. At the same time, during testing the physical model of the power plant, effects characterized by incomplete combustion or extinction during propellant combustion were revealed and also the possible development of unstable dynamic processes during the combustion products flow in the solid-propellant rocket power plant chamber was shown.

3. Based on the theoretical determination of the unsteady combustion processes parameters in the test sample chamber during the flow of combustion products, the possibility of working process instability (self-oscillations) in the power plant was shown.

4. The main possible directions of modern research of working process instability in a power plant are identified: mechanisms identification for the development of pressure oscillations in the combustion chamber, analysis and modeling of phenomena associated with propellant ignition, combustion, and heat transfer; analysis of resonant damping in a power plant; optimization of the plant chamber design in order to reduce the level of pressure oscillation amplitudes.

Contributions of authors: conceptualization, methodology – **Olexiy Nikolayev;** formulation of tasks, analysis **– Olexiy Nikolayev, Inna Bashliy;** development of model, software, verification **– Inna Bashliy;** analysis of results, visualization **– Inna Bashliy;** writing – original draft preparation, writing – review and editing **– Inna Bashliy.**

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

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РОЗВИТОК І ТЕСТУВАННЯ ВІСЕСИММЕТРИЧНОЇ МОДЕЛІ ТВЕРДОПАЛИВНОЇ ЕНЕРГЕТИЧНОЇ УСТАНОВКИ НА РЕЖИМАХ ДИНАМІЧНОЇ НЕСТІЙКОСТІ КАМЕРИ ЗГОРЯННЯ

О. Д. Ніколаєв, І. Д. Башлій

Інноваційне використання енергетичних ресурсів на місці планет далекого космосу є технологією, що припускає значне прискорення темпів освоєння космічного простору на основі проєктування ракетних енергетичних установок, зокрема, для місячних посадкових модулів при використанні (Lunar Regolith) палив. При використанні таких місцевих палив на основі вогневих випробувань розробленої фізичної моделі енергетичної установки посадкового модулю виявлено ефекти, що характеризуються вихроутворенням продуктів згоряння, коливаннями тяги, неповнотою згоряння або згасанням при горінні палива, а також можливим розвитком нестійких динамічних процесів при течії продуктів згоряння в камері твердопаливної ракетної енергетичної установки. Недопустимі стрибки тиску та різке зростання локальної температури продуктів згоряння можуть призводити до порушення міцності та руйнування конструкції камер згоряння ракетних енергетичних установок, переходу на критичний режим роботи ракетної енергетичної установки. На основі теоретичного визначення параметрів нестаціонарних процесів у камері згоряння тестового зразка палива при течії продуктів згоряння показана можливість реалізації такого типу нестійкості робочого процесу (автоколивань) в енергетичній установці. Проведено чисельне визначення термодинамічних характеристик енергетичної установки, що використовує таке металізоване паливо, а також виконано попередній аналіз експериментальних і розрахункових параметрів акустичних коливань (тяги, динамічних складових тиску, осьової швидкості). Визначено основні можливі напрямки сучасних досліджень нестійкості робочого процесу в енергетичній установці з паливом із місячного реголіту, а саме: виявлення механізмів розвитку коливань тиску в камері згоряння, аналіз і моделювання явищ, пов'язаних із загорянням палива (у тому числі, затримкою займання), горінням, теплопередачею; аналіз резонансного демпфування в енергетичній установці; розробка методів оптимізації конструкції камери установки з метою зниження рівня амплітуд коливань тиску; вивчення ролі горіння алюмінієвих крапель в алюмінізованому паливі в реалізації внутрішньої нестійкості енергетичної установки.

Ключові слова: твердопаливна енергетична установка; вихроутворення продуктів згоряння; вогневі випробування; коливання тяги; нестійкість робочого процесу; динамічні складові тиску; акустичні коливання.

Ніколаєв Олексій Дмитрович – канд. техн. наук, старш. наук. співроб., Інститут технічної механіки Національної академії наук України і Державного космічного агентства України, Дніпро, Україна.

Башлій Інна Дмитрівна – канд. техн. наук, старш. наук. співроб., Інститут технічної механіки Національної академії наук України і Державного космічного агентства України, Дніпро, Україна.

Olexiy Nikolayev – PhD, Senior Researcher, Institute of Technical mechanics NASU and SSAU, Dnipro, Ukraine,
e-mail: odnikolayev@gmail.com, ORCID: 0000-0003-0163-0891, Scopus Author ID: 6506809669.

Inna Bashliy – PhD, Senior Researcher, Institute of Technical mechanics NASU and SSAU, Dnipro, Ukraine,
e-mail: ibloha@i.ua, ORCID: 0000-0003-0594-9461, Scopus Author ID: 57563635900.