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VALIDATION OF METHODS FOR INCREASING THE EFFICIENCY OF DETONATION JET ENGINES

A fundamentally new direction in the development of rocket and space technology is the introduction of jet engines operating on the detonation principle of energy conversion in the working body. The use of detonation fuel combustion makes it possible to increase the thermodynamic efficiency of the engine and the thermodynamic efficiency of fuel combustion. Detonation is a hydrodynamic wave process involving the propagation of an exothermic reaction zone in a substance at supersonic speed. The detonation wave is the main shock wave behind the front of which a chemical reaction is continuously initiated by heating during adiabatic compression. A feature of this process is the large pressure drop before the detonation wave and in the induction zone, where the reaction occurs. The completeness of the combustion of the fuel mixture in the chambers in the detonation mode can be significantly increased by the occurrence of large pressure and velocity gradients. The problem of increasing the efficiency of jet detonation engines should be solved in the complex of structural synthesis using the accumulated knowledge about jet engines with deflagration fuel combustion. The purpose of the work is to obtain the results of studies of the defining characteristics: the development of mathematical models of the kinetics of gas-dynamic and thermal processes in the detonation combustion chamber with aerodynamic regulation; taking into account the composition and properties of the gas in the working environment of the chamber; modeling of work processes in the flow part of the engine; study of the mechanism of self-oscillations in the chamber based on kinematic patterns of gas movement; development of methods of experimental measurements of detonation flows for verification of calculation models; and improvement of the engineering methodology for calculating detonation combustion chambers with aerodynamic regulation of a detonation jet engine for a given power. Based on the results of theoretical and experimental studies, an engineering method for chamber calculation is proposed. Mathematical models of gas-dynamic and thermal processes in a detonation combustion chamber with aerodynamic regulation, which take into account the ratio of air to fuel consumption, are proposed, and allow determining the properties and composition of combustion products. Calculated equations were obtained for determining the frequency of oscillations in the detonation combustion chamber taking into account aerodynamic regulation. A method was developed for calculating the kinetics of gas dynamic and thermal processes in the detonation combustion chamber depending on the coefficient of excess air with aerodynamic regulation. Comparing the changes in the position of the flame front under the conditions of different injection distances, it was determined that for the same injection scheme but different cavity configurations, the position of the flame front has the same tendency as the change in the equivalence coefficients, which is related to the power igniter discharge and the medium of the flow field inside the cavity. Experimental studies on the characteristics of detonation engines and their implementation are relevant for the introduction of the latest innovative technologies in the rocket and space industry in Ukraine.

***Keywords**: detonation engine; mathematical simulation; specific heat flow; air-mode detonation engine.*

Introduction

The subject of the study is the modeling of processes occurring in a direct- current jet engine with detonation conversion of the chemical energy of the working body into the kinetic energy of the jet. The paper highlighted the main methods of increasing the efficiency of detonation jet engines:

- Improvement of the design of the combustion chamber helps increase efficiency, which includes optimization of the shape of the chamber, use of advanced materials, ensuring uniform mixing of fuel.

- Introduction of an afterburner that injects additional fuel into the nozzle diffuser.

- The introduction of engines with a variable cycle allows you to adjust the parameters of the engine depending on the flight conditions, optimizing the performance of the engine in a wide range of altitudes and speeds, which leads to an increase in efficiency.

- Implementation of an effective cooling system will increase overall efficiency.

- Implementation of advanced control systems and algorithms optimize engine performance based on different operating conditions.

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The purpose of the work is to obtain the results of studies of the defining characteristics: the development of mathematical models of the kinetics of gas- dynamic and thermal processes in the detonation combustion chamber with an aerodynamic valve and taking into account the composition and properties of the gas in the working environment of the chamber; modeling of work processes that take place in the flow part of the engine; study of the mechanism of self-oscillations in the chamber based on kinematic patterns of gas movement; development of methods of experimental measurements of detonation flows for verification of calculation models; refinement of the engineering methodology for calculating detonation combustion chambers with an aerodynamic valve of a direct- flow air-jet engine for a given thermal power [1].

Materials and methods of research

The subject of the study is the modeling of processes that occur in a direct-flow jet engine with detonation conversion of the chemical energy of the working body into the kinetic energy of the jet. The purpose of the work is to obtain the results of research of gas-dynamic and thermal processes in a direct-flow air-jet detonation chamber with an aerodynamic valve. One of the tools for solving such a problem is the method of a numerical experiment using mathematical modeling technologies. At an extremely high rate of energy release from the detonation combustion of fuel components, the traction and impulse characteristics of the engine are significantly increased, the prerequisites are created for simplifying its design, reducing dimensions and mass, which allows to achieve structural perfection of detonation engine installations. The purpose of the work is to obtain the results of studies of the defining characteristics: the development of mathematical models of the kinetics of gas-dynamic and thermal processes in the detonation combustion chamber with an aerodynamic valve and taking into account the composition and properties of the gas in the working environment of the chamber [2, 3, 5], modeling of work processes that take place in the flow part of the engine; study of the mechanism of self-oscillations in the chamber based on kinematic patterns of gas movement, development of methods of experimental measurements of detonation flows for verification of calculation models [4, 6, 7], improvement of the engineering methodology for calculating detonation combustion chambers with an aerodynamic valve of a direct-flow air-jet engine for a given power.

Results and Discussion

Based on the results of theoretical and experimental studies, an engineering method of chamber calculation is proposed, mathematical models of gas-dynamic and thermal processes in a detonation combustion chamber with an aerodynamic valve are proposed, taking into account the ratio of air and fuel consumption, allowing to determine the properties and composition of combustion products [3, 4, 7].

Models on opposite rotation are characterized by variations an the intensity of the wave between collisions, which has a strong local effect on the operation of the injector. However, understanding the mechanisms that control the evolution from one regime on another given the physical parameters of injection (mass flow rate, mixture ratio, liquid velocity during injection) provides knowledge about the Characteristics of propellant mixing efficiency considering the injector.

From the point of view of the operating zone for air in atmospheric exhaust conditions, the achievement of sustained detonation cycles is primarily dependent on fuel and oxidizer pressure. The air pressure in the main line controls the speed of the air jets entering the premixing chamber, affecting the intensity of the central vortex, which serves as an aerodynamic valve for the inflow of hydrogen and the quality of mixing fuel and air. For line pressures above 6.7 bar, no operating mode is detected, while in the intermediate oxidizer pressure range (between 4.7 and 6.7 bar) proper engine operation depends on fuel line pressure. Regimes with a set pressure in the fuel line above 7.7 bar led to stable detonation cycles. In the low range of oxidizer pressure (below 4.7 bar), the equivalence ratio becomes a decisive factor.

This work is an experimental demonstration of a new detonation direct-flow combustion chamber technology for which a steady pressure increase can be achieved at thermal equilibrium. The detonation direct- flow combustion chamber uses an actively controlled air intake valve with passively modulated fuel injection, such that the operating frequency of the device is determined by the set frequency of the valve. This configuration provides greater control over combustion chamber operation compared to passive valves and valveless resonant pulse combustion chambers and provides durability and efficiency.

The main collection of information and control of the test process was carried out according to the schematic diagram shown in Figure 1. The test of the operation of the engine with an oncoming air flow up to Mach 6 for 120 seconds was carried out on the bench set shown in Figure 2. The selection and use of the ejector amplifier, which was studied in work [7] shows the dependence on the length shown in Figure 3. An increase in the length of the thrust booster ejector leads to an increase in the duration of the stage of detonation products flowing out of the flow part of the engine and determines an increase in the thrust impulse. A schematic representation of the combustion chamber is shown in Figure 4.

Solving the problem of structural synthesis from the point of view of choosing the composition of the main subsystems and elements, developing a scheme, designing a

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combustion chamber of a detonation jet engine, developing methods for evaluating the main characteristics of a detonation jet engine at the design stage. To solve the problem, we used expert analysis using computer testing methods - mathematical modeling using CFD technologies (ANSYS Fluent package). During the numerical simulation, a detailed picture of the formation and propagation of the detonation wave front was obtained. Analysis of the obtained results showed that the front of the detonation wave is a set of triple configurations that constantly change their position in time and space. Figure 5 shows the simulation of fuel distribution for the case of a conventional cavity chamber and a cavity chamber with a back wall. Figure 6 shows the simulation of the velocity and pressure distribution in the calculation domain of the combustion chamber model.

The lower limit of the equivalence ratio increases with increasing air pressure and decreases with increasing fuel pressure. This phenomenon is the result of the principle of traction. Higher air pressure results in a stronger premix chamber vortex flow, while higher fuel pressure enhances the ability of the fuel jet to overcome the vortex barrier. As a result, the speed of the fuel jet penetrating the aerodynamic valve increases with fuel pressure and decreases with air pressure. This in turn affects fuel/air mixing in the premix chamber, with a higher fuel jet velocity providing improved mixing and, as a result, a lower global equivalence ratio requirement for detonation.

This work is an experimental demonstration of a new detonation jet engine technology for which a steady increase in pressure can be achieved at thermal equilibrium. This detonation combustion chamber uses an actively controlled air intake valve with passively modulated fuel and oxidizer injection, so that the operating frequency of the device is determined by the set frequency of the valve, experimental confirmation took into account the geometry of the inlet diffuser and the inlet angle at different Mach numbers. This configuration provides greater control over combustion chamber operation compared to passive valves and provides the durability required for implementation in practical applications. The proposed active valve technology provides a direct path to transition from research-type devices to practical detonation engine applications by addressing key challenges inherent in existing detonation combustion technologies.

The results of research show that detonation combustion of environmental fuels requires higher initial mass flows and temperatures, pre-initiation of fuel ignition before the arrival of the detonation wave requires special conditions in relation to the stabilization mechanism of the detonation of the limit cycle. The dependences of the speed of the pressed detonation wave on the distance to the initiation point are obtained. The dependence of the size of the detonation cell in a cylindrical damping wave on the value of its velocity is established. A study evaluating the dynamic response of the injector and turbulent mixing medium to demonstrate the importance of ignition delay with respect to these other mechanisms.

Conclusions

Calculated equations were obtained for determining the frequency of oscillations in the detonation combustion chamber considering the aerodynamic valve, a method was developed for calculating the kinetics of gas dynamic and thermal processes in the detonation combustion chamber depending on the coefficient of excess air regulated by the aerodynamic valve. Experimental data are used to confirm the two-dimensional model, which in turn provides a basis for evaluating the performance of the reduced one- dimensional model. It was decided that the higher the pressure in the controlled system, the greater the free volume, the faster the adjustment speed of the actuator, and the greater the adjustment of the gas flow. Comparing the changes in the position of the flame front under the conditions of different injection distances, it was determined that under the same injection scheme, but different cavity configurations, the position of the flame front has the same tendency as the change in the equivalence coefficients, where the limit of lean blowing in the chamber combustion, when the short-range injection condition reaches a near- purge state, this is because the ignition in the cavity is greater than the flame stabilization in the combustion chamber, which is related to the power of the igniter discharge and the flow field environment inside the cavity [1 - 9]. The conducted experiments confirm the correctness of the important technical. Decisions made and confirmed the increase in the efficiency of the thermodynamic cycle by 20-35% in comparison with existing analogues on deflagration combustion. This paper presents and analyses experimental results for a model combustor operated with gaseous hydrogen and oxygen. Dynamic measurements of wall pressure and high-speed video recordings allows determination of the most favorable conditions for the detonation propagation and the most efficient regimes of operation. The implemented techniques will help to analyze other test runs and to obtain model characteristics in a wide range of conditions. The data will be used in simulations to further evaluate the efficiency and loss factors.

Experimental studies of the characteristics of detonation engines are relevant and involve the creation of a specialized laboratory and fire test stands for the rapid introduction of the latest technologies in the rocket and space industry.

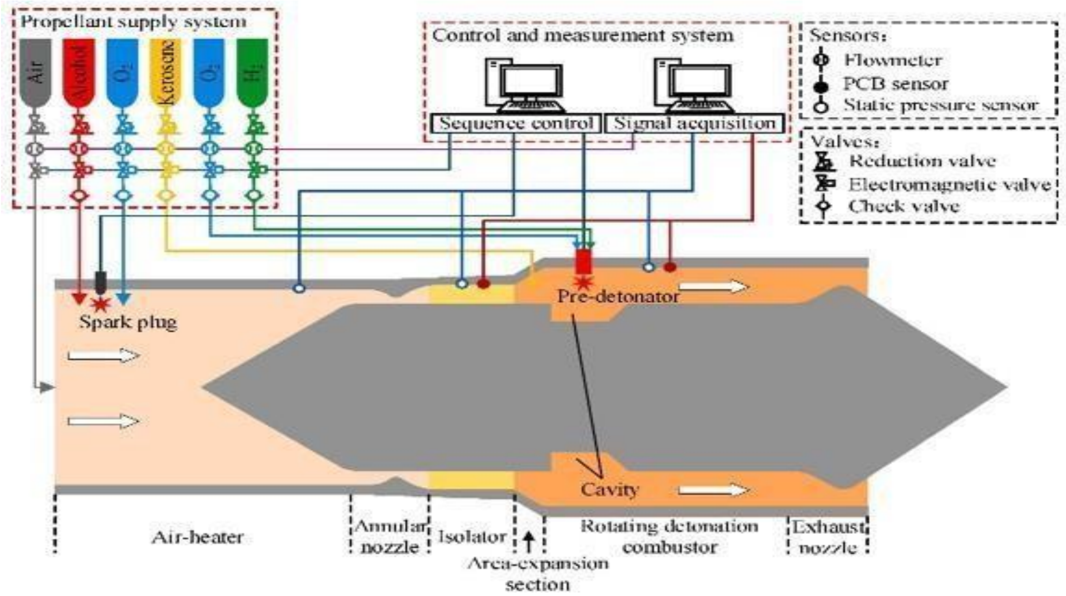

Fig. 1. Schematic diagram of the experimental system [5]

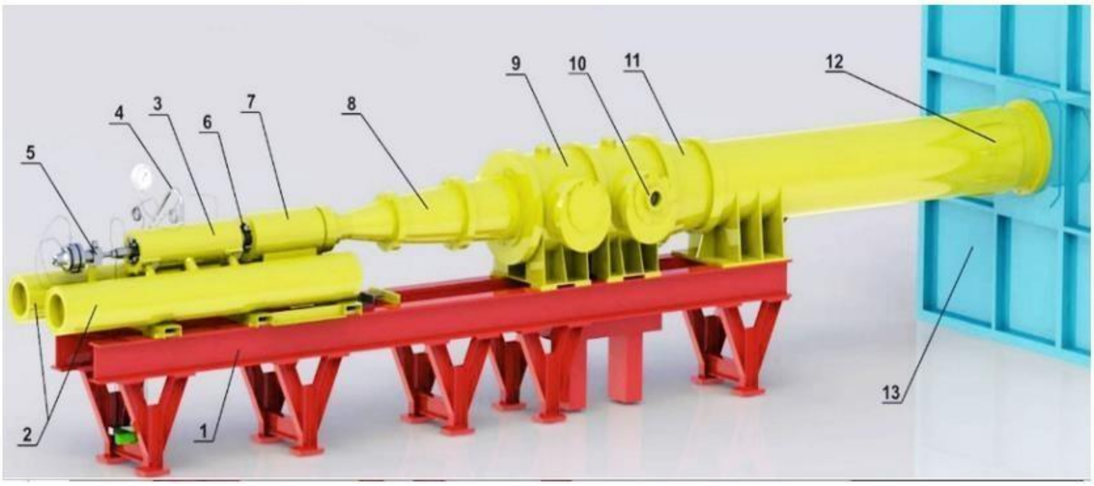

Fig. 2. Experimental setup for determining the characteristics of a direct- flow air-jet detonation engine [1]: 1 – frame; 2 – container for storing compressed air with heaters; 3 – the main fore-chamber; 4 – compressed air supply pipeline; 5 – remote quick-acting valve; 6 – connecting pipeline; 7 – auxiliary pre- chamber; 8 – replaceable part of the nozzle, 9 – the working part, where the direct-flow air-jet detonation engine is placed; 10 – the optical window for visualizing the process; 11 – confusor; 12 – exhaust diffuser; 13 – sound absorption chamber

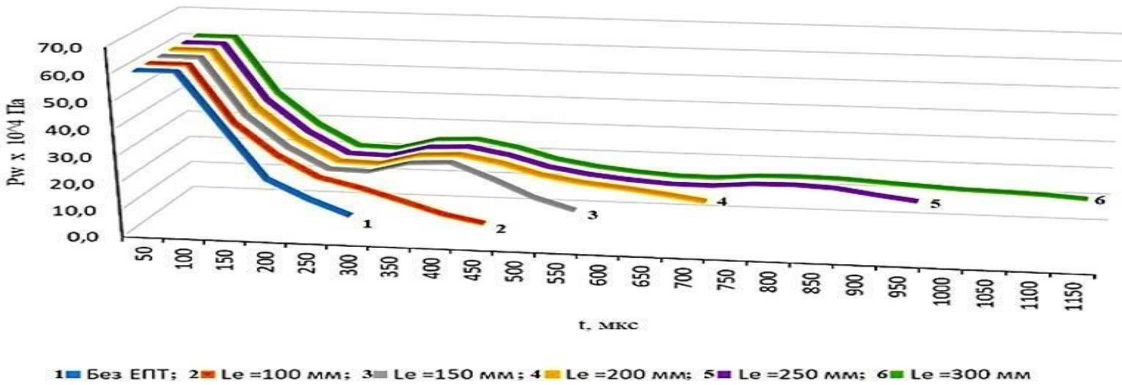

Fig. 3. Dependence of pressure change over time on the traction wall of the detonation chamber when using cylindrical ejector thrust amplifiers of different lengths: 1 – without using the ejector thrust amplifier; 2 – using an amplifier with a length of 100 mm; 3 – using an amplifier with a length of 150 mm; 4 – using an amplifier with a length of 200 mm; 5 – using an amplifier with a length of 250 mm; 6 – using an amplifier with a length of 300 mm [7]

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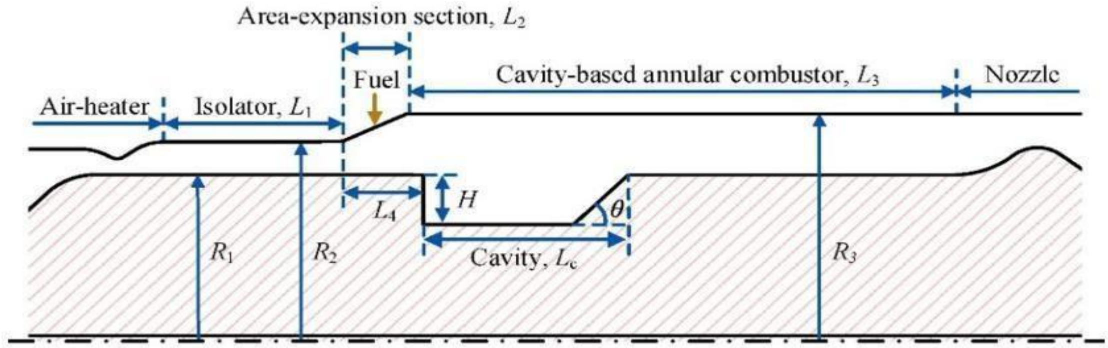

Fig .4. Structural diagram of the designed ram-RDE model [5]

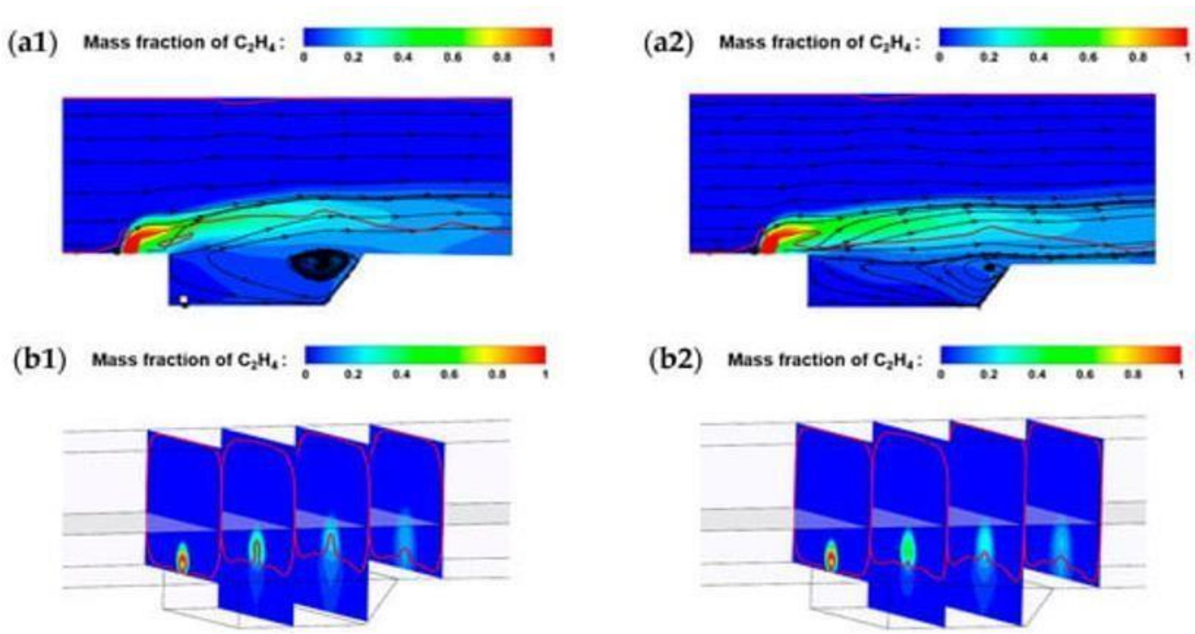

Fig. 5. Visualization of fuel distribution for the case of a conventional cavity chamber (a1, b1) and a cavity chamber with a rear wall (a2, b2), with an equivalence factor of 0.2 [4]

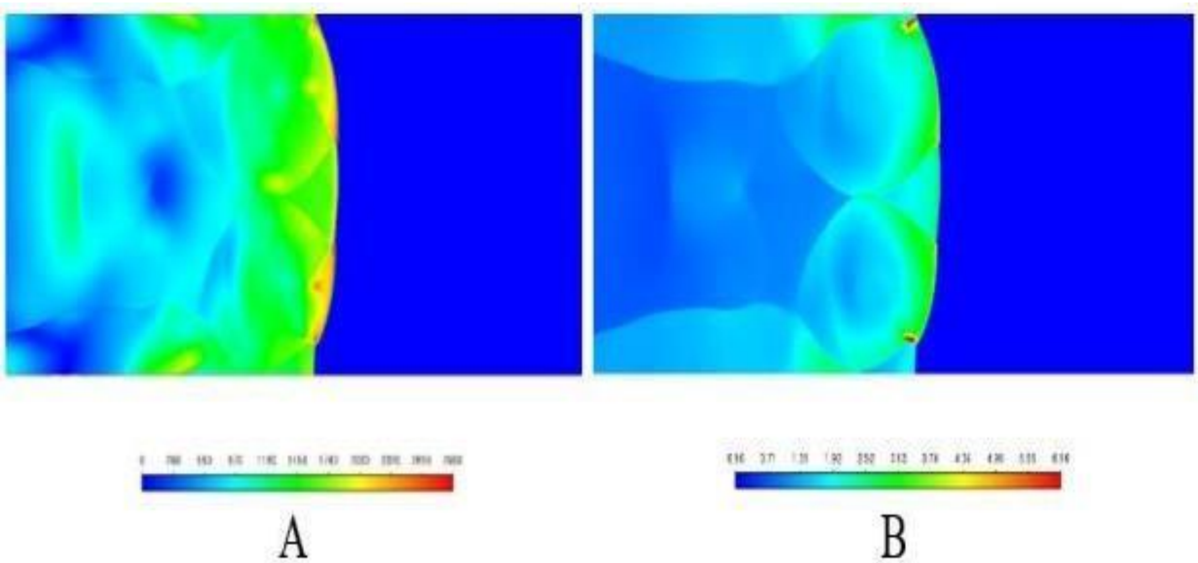

Fig. 6. Velocity and pressure distribution in the calculation domain of the combustion chamber model:
A – Velocity distribution in the calculation area, m/s; B – Pressure distribution in the calculation area, MPa [1]

Conflict of Interest

The author 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 work has associated data in the data repository.

Use of Artificial Intelligence

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

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ВАЛІДАЦІЯ МЕТОДІВ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ДЕТОНАЦІЙНИХ РЕАКТИВНИХ ДВИГУНІВ

В. В. Столярчук

Принципово новим напрямком розвитку ракетно-космічної техніки є впровадження реактивних двигунів, що працюють на детонаційному принципі перетворення енергії робочого тіла. Застосування детонаційного спалювання палива дозволяє підвищити термодинамічний коефіцієнт корисної дії двигуна і термодинамічний коефіцієнт корисної дії згоряння палива. Детонація — гідродинамічний хвильовий процес поширення зони екзотермічної реакції в речовині з надзвуковою швидкістю. Детонаційна хвиля є основною ударною хвилею, за фронтом якої безперервно зініціюється хімічна реакція внаслідок нагрівання при адіабатичному стисненні. Особливістю цього процесу є великий перепад тиску перед хвилею детонації і в зоні індукції, де відбувається реакція. Повнота згоряння паливної суміші в камерах при детонаційному режимі згоряння може бути значно підвищена за рахунок виникнення великих градієнтів тиску і швидкості. Проблема підвищення ефективності реактивних детонаційних двигунів повинна вирішуватися в комплексі структурного синтезу з використанням накопичених знань про реактивні двигуни з дефлаграційним спалюванням палива. Метою роботи є отримання результатів досліджень визначальних характеристик: розробка математичних моделей кінетики газодинамічних та теплових процесів у камері детонаційного горіння з аеродинамічним регулюванням; врахуванням складу та властивостей газу у робочому середовищі камери; моделюванні робочих процесів в проточній частині двигуна; дослідження механізму автоколивань в камері на основі кінематичних закономірностей руху газів; розробка методів експериментальних вимірювань детонаційних потоків для перевірки розрахункових моделей; вдосконалення інженерної методики розрахунку камер детонаційного горіння з аеродинамічним регулюванням детонаційного реактивного двигуна на задану потужність. На підставі результатів проведених теоретичних та експериментальних досліджень запропоновано інженерний метод розрахунку камер, запропоновані математичні моделі газодинамічних та теплових процесів у камері детонаційного горіння з аеродинамічним регулюванням, що враховують співвідношення витрат повітря та палива, дозволяють визначити властивості та склад продуктів згоряння. Отримані розрахункові рівняння для визначення частоти коливань у камері детонаційного горіння з урахуванням аеродинамічного регулювання, розроблено метод розрахунку кінетики газодинамічних та теплових процесів у камері детонаційного горіння залежно від коефіцієнта надлишку повітря з аеродинамічним регулюванням. Порівнюючи зміни положення фронту полум’я в умовах різних відстаней впорскування було визначено, що за тієї самої схеми впорскування, але різних конфігурацій порожнини, положення фронту полум’я має ту саму тенденцію, що й зміна в коефіцієнти еквівалентності, що пов’язано з потужністю розряду запальника та середовищем поля потоку всередині порожнини. Експериментальні дослідження характеристик детонаційних двигунів та їх впровадження є актуальними, для впровадження новітніх інноваційних технологій у ракетно-космічну галузь України.

Ключові слова: детонаційний двигун; математичне моделювання; питома теплова витрата; прямоточний повітряно-реактивний детонаційний двигун.

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