An experimental study of the combustion of paraffin and ceresin with the addition of metal-organic compounds in an oxygen stream

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Abstract. Experimental studies of the combustion of experimental samples of ceresin and paraffin with the addition of metal-organic compounds in a gaseous oxygen flow were performed. The tests were carried out at a pressure of 8.5 to 10.5 bar and an oxygen flow velocity of 10.5 m/s. An increase in specific impulse of 10% was obtained for samples based on ceresin and from 6 to 18% for samples based on paraffin.

1. Introduction
The hybrid engine facilities (HRE) working on solid fuel (SF) and liquid or gaseous oxidizer [1-6] are a promising direction in the developing rocket-engine technology to provide the long-term high-speed flight. It is predicted that hybrid engine systems are going to find wide application, including the control in orbital flight on upper stages, tactical and strategical rocket systems. Hybrid rocket engines combine the advantages of SPRE and LPE and, at the same time, do not have many disadvantages. The specific energy-mass characteristics of the hybrid rocket engines put them in between the LPE on cryogenic fuels and SPRE. At the same time, the hybrid rocket engines demonstrate higher values of the specific pulse than SPRE owning to the fuels with the bigger energy store. The most important advantage of the hybrid engine is the wide range of draught module control and the possibility of multiple engine ignition and cutoff during one flight. Utilization of thermoplastic materials as the major component of the fuel for the hybrid engines enables to use modern additive technologies for the development and production of charges for these engines, which essentially decreases the cost of the development and production of these engine charges. All these advantages make the hybrid engines very promising in for the rocket equipment in the XXI century.

Creation of the energy-intensive oxygen-free solid fuels with high combustion rate and provision of their high combustion efficiency in the gaseous oxidizer flow is a key challenge in the HRE development. In this work we investigate the effect of energy-intensive additives in the form of metal-organic compounds on the thrust characteristic of hybrid combustion chamber on paraffin and ceresin with oxygen as an oxidizing agent.
2. Experimental setup for investigation of solid fuel combustion in the gaseous oxidizer flow

The experimental setup of ITAM SB RAS was used to perform experimental investigations on the definition of the specific impulse of hybrid axisymmetric combustion chamber. The setup schematic is shown in figure 1. The setup consists of a flame heater 1, prechamber 2, subsonic nozzle 3, elliptical cowl 4, solid fuel sample 5, pylon 6, combustion chamber 7, output sonic nozzle 8 and spark plug. The outlook of the setup is shown in figure 2. The prechamber and input nozzle are purposed to create a uniform oxidizer flow with the specified pressure and velocity at the combustion chamber (CC) entrance. The internal diameter of the combustion chamber is 40 mm the length is 400 mm. Output sonic nozzle diameter is 9 mm. In the combustion chamber, on the pylon, there is the sample 5 of the studied solid fuel made as a cylinder of 21 mm in diameter and 40 mm in length. Ahead of the sample there is the elliptical cowl to form the uniform flow around the sample. To initiate the combustion process, the flame heater is used; some hydrogen (3 g/s) is supplied into the prechamber for the 150 ms flow temperature jump at the nozzle exit up to 2000 to 2200 K. Then the flame heater is cutoff, and the gaseous oxygen of room temperature is supplied to the combustion chamber entrance, and then the self-sustaining combustion of solid fuel takes place in the oxidizer flow. Combustion and carry-away of the solid-fuel sample mass occur only on the external surface of the sample. The typical time of combustion is 1.25 second, which is sufficient to determine the variation of the sample mass, the sample size variation is insignificant and makes almost no effect on the flow parameters on the sample surface. The total pressure necessary for calculating the specific impulse is measured in the output section of the combustion chamber.

3. Method of experimental result processing

The average mass flow rate of the sample within one regime is defined by the formula

\[ Q_{sf} = \frac{\Delta m}{t_{comb}} \]  

where \( \Delta m \) is the measurement of the sample mass within the regime, \( t_{comb} \) is the sample combustion time. The variation of the sample mass \( \Delta m \) is determined by means of the control weighting of the sample before and after the start on the laboratory balance, its accuracy is 0.02 g. The sample combustion time is preset by the oxidizer supply time in the combustion chamber.

To evaluate the efficiency of solid fuel according to the results of experiments, the specific impulse of the output sound nozzle \( I_{sn} \) is calculated by the formula

\[ I_{sn} = \frac{J_{sn}}{Q_g} \]
where: $J_{sn}$ is the impulse of the output sound nozzle; $Q$, g/s is the total mass flow rate of oxidizer and solid fuel; $g$ is the gravity acceleration.

To calculate the impulse of the output sound nozzle, the expression of the jet impulse in terms of the Mach number and pressure in the critical section of the nozzle is used

$$J_{sn} = S_{cs} P_{cs} M_{cs}^2 \gamma_{cs} + S_{cs} (P_{cs} - P_{atm})$$

(3)

where: $S_{cs}$ is the area of the critical section of the sonic nozzle, $P_{atm}$ is the pressure in the chamber into which the outflow occurs, $P_{cs}$ is the static pressure in the critical section of the sonic nozzle, $M_{cs}$ is the Mach number in the critical section of the sonic nozzle in these experiments, it was assumed that $M_{cs} = 1$, $\gamma_{cs}$ is the adiabatic index determined using the “Terra” thermodynamic calculation program for the theoretical composition of the gas flowing out of the nozzle. The error in determining the specific impulse of a sound nozzle by this method does not exceed 3%.

4. Results of solid fuel combustion tests in the oxygen flow

The tests were carried out at a pressure of 8.5 to 10.5 bar and an oxygen flow velocity of 10.5 m/s. In the experiments, the burning rate of solid fuel samples and the specific impulse of the output sound nozzle were determined. The experimental compositions are based on paraffin and ceresin with the addition of the following compounds: Ni(AG)$_2$(NO$_3$)$_2$, LaFeCuGly [7], NaBH$_4$ [8]. The mass fraction of Ni(AG)$_2$(NO$_3$)$_2$ and LaFeCuGly in all samples was 5%, NaBH$_4$ 10%. Additionally, a paraffin-based sample with the addition of a small amount of solid oxidizer was tested. The collective results of the tests are given in table 1.

| Sample              | Run | $P_{0\text{hot}}$, kPa | $Q$, g/s | $I$, s |
|---------------------|-----|------------------------|----------|-------|
| Ceresin             | 45  | 858                    | 5.21     | 113   |
| Ceresin+Ni(AG)$_2$(NO$_3$)$_2$ | 46  | 944                    | 4.97     | 125   |
| Ceresin+LaFeCuGly   | 47  | 939                    | 5.00     | 125   |
| Paraffin            | 40  | 894                    | > 15.92  | < 100.6 |
| Paraffin+Ni(AG)$_2$(NO$_3$)$_2$ | 41  | 1061                   | > 16.10  | < 119  |
| Paraffin+LaFeCuGly+oxidiser | 42  | 1018                   | > 17.84  | < 111.6 |
| Paraffin+NaBH$_4$   | 43  | 1008                   | > 17.26  | < 111.5 |
| Paraffin+NaBH$_4$+LaFeCuGly | 44  | 1053                   | > 17.61  | < 115.8 |

*Gly – Glycine; AG – Aminoguanidine nitrate*

Figures 2 and 3 show the time dependences of the total pressure in the output section of the combustion chamber for samples based on ceresin and paraffin, respectively. A rapid increase in pressure at $t = 0.3$ s corresponds to the initiating hydrogen flame at time $t = 0.45$ s, the hydrogen supply ceases and the combustion of the sample in the oxygen flow begins. The maximum pressure level is reached in the time interval from 0.8 to 1.55 s. It can be seen that for all samples with additives, the pressure level during combustion is higher than for pure ceresin and paraffin. The specific impulse calculation results (table 1) show that the addition of Ni(AG)$_2$(NO$_3$)$_2$ and LaFeCuGly to ceresin increases the specific impulse by 10%.

In experiments with paraffin, it was not possible to accurately measure the mass flow rate of the sample due to samples completely burned out during the run. From our previous studies, it is known that the maximum increase in the burning rate of paraffin samples was 5% for samples with the addition of Ni(AG)$_2$(NO$_3$)$_2$. Thus, if we assume that the burning rates of paraffin based samples in these experiments vary no more than 5%, we obtain the following increase in specific impulse for paraffin based samples: from 13 to 18% for the sample with Ni(AG)$_2$(NO$_3$)$_2$, from 6 to 11% for samples with LaFeCuGly + oxidiser and NaBH$_4$; and from 10 to 15% for the sample with NaBH$_4$ + LaFeCuGly.
5. Conclusion
Experimental studies of the combustion of experimental samples of ceresin and paraffin with the addition of metal-organic compounds in a gaseous oxygen flow were performed. The tests were carried out at a pressure of 8.5 to 10.5 bar and an oxygen flow velocity of 10.5 m/s. An increase in specific impulse of 10% was obtained for samples based on ceresin and from 6 to 18% for samples based on paraffin.

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Figure 2. Combustion chamber pressure. 1 – Ceresin; 2 – Ceresin+Ni(AG)$_2$(NO$_3$)$_2$; 3 – Ceresin+LaFeCuGly.

Figure 3. Combustion chamber pressure. 1 – Paraffin; 2 – Paraffin+Ni(AG)$_2$(NO$_3$)$_2$; 3 – Paraffin+LaFeCuGly+oxidiser; 4 – Paraffin+NaBH$_4$; 5 – Paraffin+NaBH$_4$+LaFeCuGly.
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