Study of heating and evaporation of metal in an inductor in relation to the problem of space debris processing and creating evaporative-type space engine

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Abstract. The work experimentally studied the evaporation of water and metal in a crucible simulating the nozzle of a space engine during induction heating, and also carried out analytical assessments of the generated jet thrust. An experimental laboratory setup is described. Measurements of the pressure created by the nozzle as a result of evaporation of the material in a vacuum were carried out. Zinc was used as the evaporated material. The experimental results are in satisfactory agreement with theoretical estimates. The results obtained are expected to be used in the development of an evaporative-type space engine with space debris as a working fluid.

1 Introduction

Problems associated with the contamination of the Earth's orbit by space debris have been worrying the scientific community since 1957, when the world's first artificial satellite was launched in the USSR. For 2021, the number of objects only accessible for observation from Earth is 21,901. According to the European Space Agency, as of January 2019, in Earth’s orbit there are about 34 thousand objects whose characteristic size exceeds 10 cm, 900 thousand objects with sizes from 1 cm to 10 cm and 128 million objects of smaller size, up to 1 mm. The number of satellites that commercial and military organizations launched into Earth orbit in 2017 exceeds the total number of launches for the period from 2000 to 2010 [1]. We can say with confidence that these numbers will increase every year. Such “cluttering” of the Earth’s orbit with space debris can lead to the formation of a “belt” of space debris around the Earth. This will be an obstacle to launching new satellites into orbit (Kessler syndrome [2]), since the speed of space debris objects in Earth’s orbit is up to 7 km/s and a collision of a spacecraft with space debris, even 1 cm in size, will have fatal consequences.

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Thus, the problem of disposal or processing of space debris is, in fact, vitally important for the space industry [3-7].

To create thrust when moving in space, two resources are needed - energy and mass. The problem with energy resources is, in principle, solvable. Energy (up to several MW) can be obtained using solar panels, but if you use a nuclear reactor, you can get up to several hundred MW at your disposal. With a source of mass, without which it is impossible to obtain a thrust impulse, everything is much more complicated - the mass has to be delivered from the Earth. In this regard, the thought arises that it is more reasonable to use space debris as a source of mass to create thrust for spacecraft.

Naturally, this approach requires the creation of some new universal rocket engine (Universal Rocket Space Engine, URSE). The main idea - using space debris as propellant for thermal or electric rocket engine [8,9].

The structural scheme of such a universal rocket engine (URSE) may look like this. The crushed debris particles fall into the crucible, which is a source of high-temperature steam. The working fluid in the crucible is intensely heated, melts, evaporates, then either directly flows into space through the nozzle, or first enters the plasma accelerator and is accelerated to the required speed. Space debris, when placed in a crucible, must not just melt, but reach the stage of intense evaporation. Otherwise, the draft created by the escaping steam will be too small. The main advantage of such an engine is almost complete omnivorousness. Any substance can serve as a working fluid for it if its vapor pressure at temperatures of 2300 – 2500 K is of the order of $10^4$ Pa.

## 2 Evaporative engine concept

We are considering the so-called evaporative engine. The engine works as follows (see fig.1). The working medium 3 in the working chamber 1 is heated by an inductor 2 to the boiling point in the chamber and the vapors 4 are ejected through the nozzle (with mass flow $G$) creating jet thrust $F$. Induction heating is a popular and generally accepted heating method known to be used in various fields of technology [10,11]. We suggest using induction heating for the following reasons:

1) Space debris is mostly metal, mostly aluminum.
2) Induction heating is non-contact, which significantly simplifies the design of the working chamber.
3) Space debris consisting of non-conducting inclusions can be heated inside a conducting chamber made, for example, of graphite.

Fig. 1. shows the scheme of an evaporative engine.

![Fig. 1. Scheme of an evaporative engine. 1 – working chamber, 2 – inductor, 3 – fragments of space debris, 4 - vapors.](image)
The working chamber can be either non-conductive for heating metal fragments or conductive, in which case heating and evaporation of plastics is possible. In our experiment, we used a graphite crucible as it is more universal. Graphite has a high melting point of 3890°C and therefore it is advisable to use it as a material for a conductive heated chamber. Graphite also has a relatively low electrical conductivity with $s = 7.7 \times 10^4$ S/m.

### 3 Experimental setup

We developed an experimental setup with the following design (Fig. 2). We placed the heated metal in a graphite crucible 4. The crucible was placed in an inductor 3 and mounted on a stand 10 with a strain gauge 11 measuring weight using scales 1. The entire structure was enclosed in a low pressure chamber 9. A transparent cover 6 was located on top. Current is the only controlled parameter and we determined it using current transformer 7 and oscilloscope 8. The air from the chamber was pumped out using fore vacuum pump 2.

We used induction installation 6 with the following parameters: frequency 30-60 kHz, inductor current - up to 620 A, power - up to 5 kW. With our inductor consisting of 5 turns with a diameter of 50 mm, at maximum power the installation consumes 22 A at a voltage of 220 V. The inductor was a copper tube with pumped water. The fore vacuum pump power was 550 W and allowed us to achieve a pressure of 1800 Pa in our chamber. We used the HX-711 strain gauge connected to an Arduino MEGA 2560 (with a display installed). The graphite crucible had the following dimensions: height 100 mm, internal diameter 20 mm, external - 24 mm.

![Fig. 2 Scheme of the experimental setup. 1 – output device with LCD display; 2 – fore vacuum pump; 3 – inductor; 4 – crucible; 5 – material; 6 – low pressure chamber cover; 7 – current transformer; 8 – inductor control unit; 9 – oscilloscope; 10 – low pressure chamber; 11 – stand; 12 – strain gauge.](image)

For theoretical estimates, it is necessary to know the power deposited into the heated sample. During induction heating, this power depends on many factors, including the size of the heated sample and the frequency of the inductor, so preliminary experiments were carried out to determine the input power. Power was determined by thermal balance. A chromel-alumel thermocouple (type K, sensitivity is 40µV/°C) was placed in the nozzle and thermocouple readings were recorded during the heating process. The signal from the thermocouple went to a thermocouple amplifier with a gain of 100, and then to a Rudnev-Shilyaev La2M5PCI analog-to-digital converter with the following characteristics: 12-bit resolution, maximum sampling frequency 400 kHz. The analog-to-digital converter was installed in a personal computer connected to the power through an isolation transformer.
Because the inductor interferes with the thermocouple, heating was performed intermittently. As the temperature increases, energy losses associated with convection and radiation increase, so it is effective to heat the sample to relatively low temperatures. Also, the matching of the inductor and the sample will change due to changes in electrical conductivity under the influence of heating.

4 Experiments and results

4.1 Determination of the characteristics of an induction heater

The heating intensity in the inductor depends on many factors, including power, frequency of current in the inductor, size and conductivity of the material. We carried out measurements of current and power consumption, as well as the dependence of frequency on current, the results are presented in Fig. 3 and 4.

4.2 Experiment on water evaporation in a graphite crucible

To evaluate the heat release in a graphite crucible, the following experiment was carried out. A graphite crucible was placed inside the inductor. The crucible was filled with water and heated by an inductor, the water evaporated, the temperature was measured by a thermocouple placed in the center of the crucible. Water mass: 20.0 g, current in the inductor – 198 A, 255 A, 318 A.

In Fig. 3 shows the water temperature during the experiment, and in Fig. 4 dependence of the mass of evaporated water on time. To obtain heat release in a graphite crucible, it is necessary to take into account that the water was first heated to 100°C (for this, the data from Fig. 3 was used).

By analyzing the graphs we can obtain the heat release in a graphite crucible:

\[ N_w = Q_w / \Delta t = h_w m / \Delta t. \]  \hspace{1cm} (1)

Where, \( N_w \) is the heating power, \( Q_w \) is the energy received, and \( m \) is the mass of boiled water out, \( \Delta t \) – time.

Let us present theoretical estimates of the generated thrust depending on the input power. Let the input power (i.e., the power used to heat the material (fuel)) be equal to \( N \). The mass flow rate of steam \( G \) can be estimated as \( G = N / h \), where \( h \) is the heat of
vaporization of the material; $S$ – crucible outlet area; $R$ – gas constant of the evaporated material. Since preliminary experiments were carried out for water. Water was chosen as a non-electrically conductive substance that was heated in a graphite crucible at the initial stage (for the case of generation of thrust by non-conducting space debris). Let's calculate the thrust when water evaporates at atmospheric pressure.

![Graph](image)

**Fig. 5.** Dependence of the water temperature from time. Inductor Current I – 198 A, 2 – 255 A, 3 – 318 A

![Graph](image)

**Fig. 5.** Dependence of evaporated water mass from time. Inductor Current I – 198 A, 2 – 255 A, 3 – 318 A. The star marks the moment when the entire volume of water heated to 100°C

Initial data: $h_w = 2.3 \times 10^6$ J/kg, $R=880$ J/(kg K), $N= 1017$ W, the diameter of the hole through which the steam flows is $d = 20$ mm, $S= 1.42 \times 10^{-4}$ m$^2$.

With these parameters, the mass flow rate of steam in the installation is:

$$G = \frac{N}{h} = 4.4 \times 10^{-4} \text{ kg/s.} \quad (2)$$

Water vapor density:

$\rho = 0.6$ kg/m$^3$,

Water vapour rate:

$$W = \frac{G}{(\rho S)} = 4.56 \text{ m/s.} \quad (3)$$

Hence the thrust created by the evaporation of water:

$$F = GW = 0.104 \text{ g.} \quad (4)$$

**Table 1.** Comparison of evaporation rate and reactive force under different heating modes.

<table>
<thead>
<tr>
<th>Mode number</th>
<th>$I, A$</th>
<th>$N_w, W$</th>
<th>Theoretical jet thrust, g/s</th>
<th>Evaporation speed, g/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>198</td>
<td>409</td>
<td>0.017</td>
<td>0.178</td>
</tr>
<tr>
<td>2</td>
<td>255</td>
<td>693</td>
<td>0.048</td>
<td>0.301</td>
</tr>
<tr>
<td>3</td>
<td>318</td>
<td>1017</td>
<td>0.104</td>
<td>0.442</td>
</tr>
</tbody>
</table>

From the data given in the table, we can conclude that it is not possible to measure the thrust, since the rate of loss of the water mass is approximately 2.2 times greater than the thrust itself.
4.3 Experiment on zinc evaporation in a graphite crucible

Since our work is preliminary in nature, we used zinc as a conductive material. Zinc is a low-melting metal with a low boiling point, which significantly weakens the requirements for the quality of vacuum in the chamber.

Let us carry out similar estimates for zinc. $P$ is the pressure in the volume where the steam flows; $M$ is its molar mass.

\[ (Zn, \ M = 65.38), \] we will carry out numerical estimates specifically for it at heating parameters corresponding to the first mode (see Table 1 below).

We assume $h = 1.74 \times 10^6$ J/kg, for zinc vapor $R = 127$ J/(kg K), $C_p = 317.9$ J/(kg K). The pressure in the chamber into which the steam flows from the crucible is assumed to be equal to $P = 1900$ Pa; electrical power used for evaporation, $N = 963$ W; the diameter of the hole through which the steam flows is $d = 20$ mm, which corresponds to $S = 1.54 \times 10^{-4}$ m$^2$.

The crucible temperature, in accordance with experimental data, is taken equal to $T = 1179$ K.

With these parameters, the mass flow rate of steam in the installation is:

\[ G = \frac{N}{h} = 5.6 \times 10^{-4} \text{ kg/s}. \] (5)

The maximum possible rate of zinc vapor flow into vacuum ($P = 0$) will be

\[ W_{\text{max}} = \sqrt{2C_pT} = 866 \text{ m/s}, \] (6)

and the maximum possible thrust created by the device is

\[ F_{\text{max}} = GW_{\text{max}} = 0.05 \ N = 48.2 \text{ g}. \] (7)

However, in our case, the outflow of steam occurs into a volume with a pressure $P = 1800$ Pa. The outflow appears to be substantially subsonic. In this case, we find the density of steam flowing from the crucible from the relation:

\[ \rho = \frac{P}{(RT)} = 0.013 \text{ kg/m}^3, \] (8)

which corresponds to the exhaust speed

\[ W = \frac{G}{(\rho S)} = 139.7 \text{ m/s}. \] (9)

This speed corresponds to the flow Mach number of 0.07, that is, the flow is essentially subsonic and the initial assumption is valid. This speed value corresponds to thrust

\[ F = GW = 8.29 \times 10^{-6} N^2 = 7.8 \text{ g}. \]

The obtained thrust value is at least in qualitative agreement with the experimental results presented below.

![Fig.6. Dependence of jet thrust on time (zinc).](image_url)

The experiment was carried out as follows. We placed the heated metal (zinc granules) into a crucible and then the air was pumped out. When the sample was heated in the
inductor to the boiling point, intense evaporation began (observed through the transparent cover) and the scales showed an increase in weight, which can be interpreted as the appearance of jet thrust. A graph of the thrust (as a function of time) obtained in the experiment is presented in fig. 6. The thrust was measured immediately after turning off the heating in order to exclude electromagnetic effects. We see that as the heating is turned off, the thrust quickly decreases, however, we have a few seconds to record it using scales.

5 Conclusions

An experimental installation simulating an evaporative space engine was developed and manufactured. An induction installation was used to heat the working medium.

Experiments were conducted to determine the characteristics of the induction heater.

The jet thrust created in the nozzle during the evaporation of the working medium (zinc) was measured. Analytical estimates of the input thermal power from the inductor and theoretical estimates of reactive thrust were carried out. The results obtained are in satisfactory agreement – the estimated value is about 8 g, the value in the experiment is about 15 g.

The results obtained can be used to create a more powerful installation. A practically significant result would be to obtain jet thrust using aluminum. Since aluminum has a significantly lower vapor pressure than zinc, it is necessary to carry out experiments at a higher temperature or at a significantly lower pressure. These are the tasks of the next stage of research.

Acknowledgements

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References