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Experimental and analytical study of metal heating and evaporation in an inductor in the context of the problem of processing space debris and creating a universal evaporative space engine

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Received September 11, 2024
Revised November 25, 2024
Accepted November 25, 2024

The processes of metal heating and evaporation in an induction heater have been studied experimentally and analytically. Jet thrust created as a result of the material evaporation in a lowpressure chamber was measured and, in addition, analytically estimated. The experimental results are in satisfactory agreement with theoretical estimates. We suppose to use the data obtained in developing an evaporativetype propulsion system with space debris as working fluid.

Keywords: space debris, space engine, heating, inductor, zinc, evaporation, jet thrust.

DOI: 10.61011/TPL.2025.03.60733.20113

Problems associated with the Earthś orbit contamination with space debris have worried the scientific community since 1957 when the USSR launched the worldś first artificial satellite. As of 2023, the number of objects accessible for observation from the Earth is more than 30,000. The total number of objects larger than 1 cm exceeds a million [1]. The speed of space debris fragments in the Earth orbit reaches 7 km/s; therefore, the spacecraft collisions with debris will have fatal consequences. Thus, the problem of disposal or recycling of space debris is extremely important for the space industry [2–4]. First, space debris may be annihilated by transforming it into plasma with a laser; second, it is possible to collect debris by using autonomous spacecraft and destroy it in the upper layers of the Earthś atmosphere [5]. To our mind, the space debris destruction is not only extremely expensive, but also an extremely irrational method. In this paper we propose to use space debris as a source of mass for creating the spacecraft thrust; this approach requires creation of a new universal rocket engine [6,7].

Here we consider the socalled evaporative engine (Fig. 1). The engine operating procedure is as follows: working fluid is heated by the induction heater to the boiling point, and vapors are ejected through the nozzle thus creating jet thrust. Induction heating is a popular and widely accepted heating method known for its applications in various technical fields [8,9]. The reasons for which we propose to use induction heating are as follows:

— space debris consists mostly of metals;

— induction heating is a contactless process which significantly simplifies the working chamber design;

— space debris consisting of nonconductive inclusions may be heated inside the electrically conductive graphite working chamber.

In this work we have examined the applicability of the concept of a rocket engine with induction heating of the working fluid in the lowpressure chamber.

The experimental setup scheme is given in Fig. 2. In ceramic nozzle *4* ($d = 14$ mm) there was placed a sample of zinc $m = 10$ g in mass. Zinc was chosen as working material because it is a lowboiling metal convenient for conducting the experiments; other lowboiling metals are either very active (potassium, sodium, cesium) or toxic in the vaporous state (mercury). Inductor *3* $d_i = 37$ mm in diameter and $h_i = 37$ mm in height was arranged around the nozzle. The nozzle was set on holder *10* attached to strain gauge *11*. To control the current, current transformer *7* and oscilloscope *8* were used. At the beginning of the experiment, air was pumped out of the lowpressure chamber to the pressure of ~ 1800 Pa, after which zinc was heated with the inductor and began to evaporate. Zinc vapor exited the nozzle

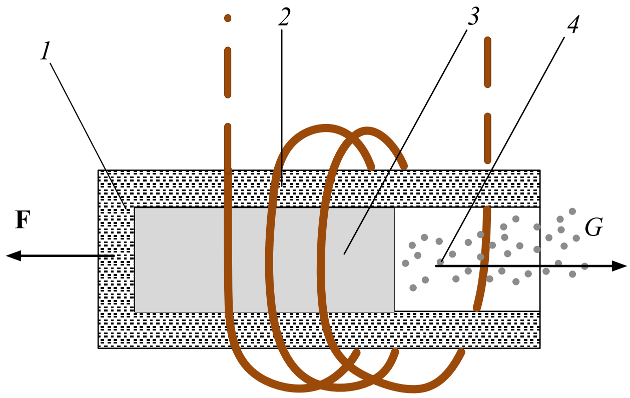

Figure 1. Schematic diagram of the evaporative engine: *1* — working chamber, *2* — inductor, *3* — space debris fragment, *4* — metal vapor, **F** — jet thrust, *G* — mass flow.

Table 1. Zinc properties (s — solid state, l — liquid state)

Parameter	T, K							
	300	400	500	600	692.73 (s)	692.73 (l)	800	1000
C_p, J/(kg · K)	389	402.6	417.6	436.1	452.7	480.3	480.3	480.3
$\rho \cdot 10^8$, $\Omega \cdot$ m	6	8	10.5	13	16	–	37.5	–

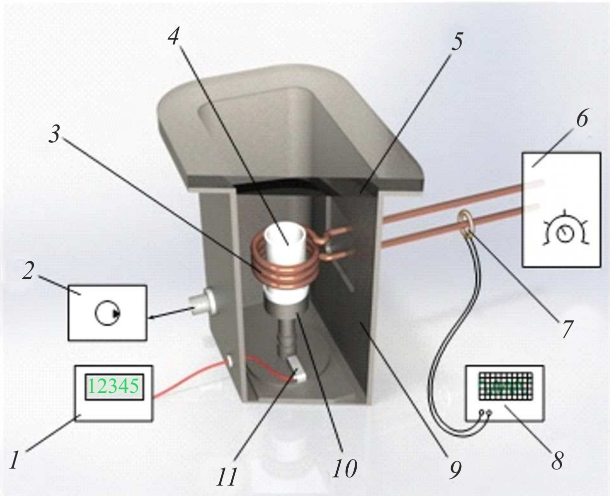

Figure 2. Schematic diagram of the experimental setup: *1* — balance, *2* — vacuum forepump, *3* — inductor, *4* — nozzle, *5* — lowpressure chamber cover, *6* — inductor control unit, *7* — current transformer, *8* — oscilloscope, *9* — lowpressure chamber, *10* — holder, *11* — strain gauge.

thus creating the thrust that was fixed by strain gauge HX-711. The gauge was connected to microcontroller Arduino MEGA 2560 which processed the data and displayed it on a digital screen. The weight measurement system was calibrated using weights G-2-210 (accuracy class 2) that are accurate to at least 0.03% (declared accuracy is 0.0003 g for the weight of 1 g). The readings spread over a minute was no more than ± 0.1 g; this value may be interpreted as the weight measurement accuracy.

To estimate power transferred to the metal, pilot experiments were carried out. Zinc was heated at the atmospheric pressure to the boiling point equal to 907 °C; in the process, temperature was measured with a chromelalumel thermocouple. The power spent on heating was estimated by using a thermogram section in the range of 880–900 °C. Average power N transferred to the metal was calculated as $N = \frac{m}{\tau} \int_{T_1}^{T_2} C_p dT$, where T_1 and T_2 are the initial and final temperatures, C_p is the heat capacity, τ is the time of heating. Table 1 presents the zinc heat capacity and electrical resistivity.

Table 2 presents the experimentally measured power transferred to the metal depending on the electric current flowing in the inductor.

Table 2. Zinc sample heating power

Mode	Inductor current I, A	Power N, W
1	255	41 ($P = 101$ kPa)
2	336	81 ($P = 101$ kPa)
3	431	205 ($P = 101$ kPa)
4	381	240 ($P = 1800$ Pa)

Note that Table 2 demonstrates just the useful absorbed power spent on heating material in the nozzle; a part of energy is lost to radiation and heating of the nozzle and air. If the pressure is lower, the absorbed power will be somewhat higher because of the absence of convection; this is demonstrated in mode 4 realized at the pressure of 1800 Pa. In addition, current induced in the heated sample depends complexly on the sample size and electrical conductivity.

Now we present theoretical estimates of the thrust created. In our case, the zinc vapor pressure is $P = 1866$ Pa (which matches the average integral pressure during the experiment); in the saturation curve, this value corresponds to 881 K (608 °C) [10]. Assume that the specific heat of zinc vaporization is $L = 1.74 \cdot 10^6$ J/(kg · K), specific heat capacity of zinc vapor is $R = 127$ J/(kg · K), $C_p = 317.9$ J/(kg · K). The nozzle diameter is 14 mm, crosssection area is $1.54 \cdot 10^{-4}$ m^2. Then the zinc vapor mass flowrate is $G = N/L = 1.38 \cdot 10^{-4}$ kg/s, and the maximum zinc vapor speed will be achieved in vacuum ($P = 0$ Pa): $V_{\max} = \sqrt{2C_pT} = 749$ m/s. Based on this, it is possible to calculate for the maximum input power ($N = 240$ W) the maximum possible jet thrust created by the device: $F_{\max} = GV_{\max} = 8.8 \cdot 10^{-2} N = 10.3$ g.

In this case, the flow is subsonic, the vapor density is $\rho = P/(RT) = 1.7 \cdot 10^{-2}$ kg/m^3. The vapor exhaust rate from the nozzle is defined as $V = G/(\rho S) = 53.8$ m/s, which corresponds to jet thrust $F = GV = 0.74$ g. At the heating power of 41, 81 and 205 W, jet thrust is 0.022, 0.085 and 0.542 g, respectively.

Since characteristics of the measuring equipment prevent measuring the jet thrust at the heating power of 41 and 81 W, an experiment was conducted to measure the jet thrust at the heating power of 240 W. To eliminate the effect of electromagnetic force, the metal was located in the center of the inductor. The uncompensated electromagnetic force arising due to upward pulling of molten metal was estimated by numerical calculations. It was found out that, when the body height changes by 3 mm (with the

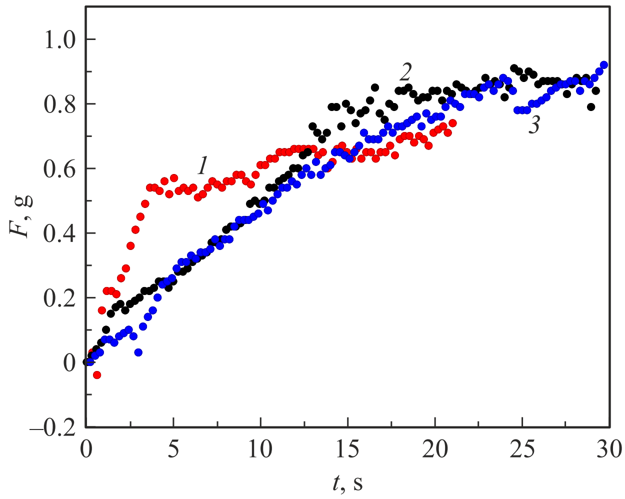

Figure 3. Jet thrust versus time at pressure $P = 1866$ Pa. Digits designate the experiment numbers. The colored figure is given in the electronic version of the article.

volume remaining the same), the upward electromagnetic force is ~ 2 mN (0.2 g), and this force reduces the balance readings. When the zinc sample was heated to boiling point, intense evaporation began (and was observed through the transparent cover), and the balance demonstrated an increase in weight, which may be interpreted as emergence of jet thrust (the actual thrust being somewhat higher than the measured one because the electromagnetic force was directed oppositely). Fig. 3 demonstrates thrust F versus time t.

Thrust averaged over the time interval under consideration is ~ 0.45 g, while the maximum one is 0.9 g; this is in satisfactory agreement with the analytical estimate. A portion of evaporated zinc settled on the nozzle walls; the zinc mass decreased during the experiment by 0.22–0.54 g. By the example of zinc, efficiency of the concept of the evaporative engine with working fluid heated by the induction method was demonstrated.

Space debris consists mainly of aluminum or steel whose evaporation at the achievable temperatures needs a lower pressure (Fig. 1). In space, this condition is met without any problems. For instance, the pressure at the ISS orbit is $\sim 9 \cdot 10^{-7}$ Pa. Thus, the temperature necessary for aluminum is below 1000 K, while that for steel is approximately 1000 K.

Acknowledgements

The authors express their gratitude to P.I. Polyakov and S.M. Yudin for assistance in preparing the article.

Funding

The study was supported by the Russian Science Foundation (project № 23-29-00911.

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] *ESA's Space Environment Report 2023* [Electronic source]. https://www.esa.int/Space_Safety/ESA_s_Space_Environment_Report_2023
[2] J. Morin, Nature, **567**, 25 (2019). DOI: 10.1038/d41586-019-00732-7
[3] S.Y. Su, Adv. Space Res., **10**, 389 (1990). DOI: 10.1016/0273-1177(90)90375-A.
[4] J.N. Opiela, Adv. Space Res., **43**, 1058 (2009). DOI: 10.1016/j.asr.2008.12.013
[5] M. Emanuelli, G. Federico, J. Loughman, D. Prasad, T. Chow, M. Rathnasabapathy, Acta Astron., **104**, 197 (2014). DOI: 10.1016/j.actaastro.2014.07.035
[6] V.V. Glazkov, O.A. Sinkevich, G.B. Shmelkov. J. Phys.: Conf. Ser., **1370**, 012036 (2019). DOI: 10.1088/1742-6596/1370/1/012036
[7] D.A. Vinogradov, V.V. Glazkov, Yu.P. Ivochkin, K.G. Kubrikov, I.O. Teplyakov, O.A. Sinkevich, J. Phys.: Conf. Ser., **2057**, 012056 (2021). DOI: 10.1088/1742-6596/2057/1/012056
[8] S. Zinn, S.L. Semiatin, *Elements of induction heating: design, control and applications* (ASM International, USA, 1988).
[9] V.E. Zinovév, *Teplofizicheskie svoystva metallov pri vysokikh temperaturakh. Spravochnik* (Metallurgiya, M., 1989). (in Russian)
[10] G.V. Samsonov, A.P. Epik, *Tugoplavkie pokrytiya* (Metallurgiya, M., 1973). (in Russian)

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