Evaporation and sparking during induction heating of metallic drops in relation to utilization of space debris

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Abstract. The paper presents the results of primary experimental studies of intense evaporation of samples made of various metals. The heating is performed with the help of induction currents, being one of the perspective ways of heating in space. Special attention is devoted to the process of intensive small drops (sparks) ejection during heating. The obtained results are supposed to be used for the design of space debris utilization systems directly at the orbit.

1. Introduction

Recently, in the industrially developed countries around the world, intensive research has been carried out on the use of metals (in particular, iron and aluminum) as fuel. In our opinion, one of the most effective and interesting areas of using metals for this purpose is associated with the recycling of space debris. As of July 2013, it was estimated that more than 170 million debris particles less than 1 cm in size were in orbit around the Earth, [1]. Such "cluttering" of the Earth's orbit with space debris may lead to destructive consequences associated with both the launch of new satellites and the operation of existing ones. Various solutions to this problem are proposed in [2]. They have a common view on space debris as a substance that must be disposed of (670,000 debris particles 1–10 cm in size and about 29,000 larger fragments).

However, in fact, space debris is a very valuable resource that can be used to maintain and correct the trajectory of spacecraft powered by ion engines. An unlimited source of energy in space is the Sun (solar batteries); for flights beyond the orbit of Mars, it is possible to use nuclear reactors with a capacity of several megawatts. However, creating the thrust, which is necessary to accelerate the spacecraft, requires not only energy, but also the mass. For this mass, one can use the vapor of various metals obtained in the evaporator by heating space debris [3]. In the future (for flights to the Moon, Mars and beyond), the material of small celestial bodies (the Moon, Mars satellites, comets) may be used as a source of mass.

In fact, we are talking about the creation of a universal rocket engine for space, the basis of which is a source of high-temperature vapor (primarily a vapor of metals) operating on space debris. The generated high-temperature vapor then serves as a working fluid for an electric jet engine, which can be used as various versions of Hall ion thrusters based on widely-used stationary plasma thrusters.
(SPT) [4]. It should be noted that high-temperature heating under zero gravity gives rise to a number of technical difficulties: 1) it is difficult to achieve effective heating and melting of small fragments of space debris under zero gravity; 2) it is necessary to prevent the release of solid and liquid phases in place with vapor into the SPT inlet; 3) in order to create a uniform temperature field it is required to organize an intensive circulation of the melt; 4) it is necessary to study the hydrodynamics of a three-phase medium (solid fragments, melt and vapor) in the volume of the evaporator during intense heating under zero gravity and to search for optimal ways to control the movement of such a medium; 5) it is required to prevent condensation of vapors of refractory components on structural elements.

The authors of this work consider the high-frequency induction heating as one of the most promising methods of heating in zero gravity. This heating method has obvious advantages over the indirect heating through the wall. It also serves, using a certain configuration of the turns of the inductor, to fix the heated material in the desired area of the heating chamber (this effect is used in the so-called levitation melting of metals [5]). The electric vortex flows arising in the liquid phase of the metal intensify the heat exchange inside the heated substance. Since the heating process is carried out at a reduced pressure, the induction discharge arising directly in the heating chamber will be the source of the primary ionization of the steam entering the SPT.

2. Experimental methods
The paper presents the results of primary experimental studies of intense evaporation of samples made of various metals.

![Figure 1. The scheme of experimental setup](image)

The heating was performed with the induced currents, which is one of the most promising methods of heating in space. The experiments were carried out using the setup presented at Fig. 1, in which the samples (usually a metal ball with a diameter of 10 mm) were placed on a ceramic support in the center of a ring inductor. The characteristic frequency of the inductor current was 60 kHz. The sample surface temperature, the maximum value of which did not exceed 2500 K, was measured by spectral pyrometry using an Ava Spec-3648 spectrometer. Video recordings of melting and evaporation were carried out using three video cameras with a shooting speed of 50, 250, and 1000 frames/s. When filming the melting process, the light filters and reflective glasses were used, which allowed observing the vortex motion on the lateral surface of the molten droplet. Ball bearing steels of the ШХ16 and 95Х18 types (US counterparts 52100 and 440B, respectively), as well as pure metals: copper, lead, nickel, were used.
as sample materials. The experiments were carried out both in an argon atmosphere and in air. The latter circumstance was due to the possible presence of an oxidizing agent in space debris.

3. Experimental results
In accordance with the well-known technique [6], the flame temperature of heated metals was determined from the angle of inclination of the linear part of their spectrum, presented in the Wien coordinates. As it can be seen from Fig. 2, the results obtained indicate the efficiency of this technique in the entire investigated temperature range (~ 1000–2500) K, regardless of the forms of melting and evaporation for various materials.

![Figure 2](image_url)

**Figure 2.** Typical emission spectrum of high-temperature samples in Wien coordinates. (a) lead, T = 2129 K; (b) copper, 1436 K; (c) steel 95X18, 2307 K; (d) Nickel, 2134 K; (e) copper, 1389 K; (f) steel IIIX15; 1667 K.
As shown by the experiments, high-temperature induction heating of metals in an oxidizing environment has specific features. The results of visual observations (Fig. 3) indicate a significant difference in the nature of evaporation (weight loss) for samples from different metals. Even steels grades ШХ15 and 95X18, similar in carbon percentage, evaporate in a completely different way during induction heating. Heating of ball-bearing steel ШХ15 is accompanied by intense sparking-emission of luminous small splashes with a diameter of 0.1–1 mm (Fig. 4). The performed X-ray diffraction analysis has shown that secondary small droplets entrained from the main mass of the melt during heating consist of liquid metal and its oxides (about 30% by mass). The speed of outgoing sparks is in the range of 0.5–3.5 m / s (Fig. 5).

The emission of sparks, contributing to an intensive decrease in the droplet mass, was observed over its entire surface formed by the oxides. It may be assumed that the heating of the melt by induction currents was carried out inside the volume bounded by a shell. Metallic vapor was generated inside this porous shell and was thrown out either through the formed passages (Fig. 3b and Fig. 6), or by explosive destruction of most of the droplet (Fig. 3c). Ultimately, in most cases, the droplets of this melt, when solidified, turned into a hollow cavity of metal oxides. For the rest of the materials used in the experiments, there was a process of “ordinary” evaporation of liquids from their outer surface, Fig. 3.

Figure 3. A characteristic appearance of evaporating drops of various metals.

a) lead, temperature $T = 2130\text{K}$; b) steel ShKh15, 1900 K; c) steel ШХ15 at temperatures above 2000 K; d) copper, 2170 K; e) nickel, 1750 K; f) steel 95X18, 2040 K.
Figure 4. Photo of secondary droplets (a) and their diameter distribution (b).

Figure 5. Photo emission of secondary drops of the melt. (a), (b) The time interval between the frames is 8 ms. (c) Dependence of the initial velocity of secondary droplet emission on their diameter.

Figure 6. Typical view of vertical (a) and horizontal (b) sections of a cooled drop.

Conclusions
The idea of using space debris as fuel for ion engines has been developed in this work. For this, the features of intense evaporation of liquid metals, ionized vapors of which are used as a working fluid, were investigated using induction heating. When heated in air, that is, in the presence of an oxidizing agent, a number of interesting physical effects associated with the sparking process (ejection of incandescent secondary droplets) into the surrounding space have been discovered. When analyzing the literature, we have not found any publications with the description of the mechanisms of such
effects, which, in our opinion, are due to intense oxidation of the surface of steel drops and heating of the melt by induced currents inside this peculiar oxide shell.

This process can seriously disrupt the operation of the SPT, which receives the metal vapor generated in the system. Therefore, in the future, it is planned to carry out a more detailed study of the evaporation and sparking process during induction heating of samples made of various materials used in space technology.

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References
[1] Morin J 2019 Nature 567 25–7
[2] Emanuelli M, Federico G, Loughman J, Prasad D, Chow T and Rathnasabapathyet M 2014 Acta Astronautica 104 197–205
[3] Glazkov V V, Sinkevich O A and Shmelkov G B 2019 JPCS 1370 012036
[4] Gorshkov O A, Muravlev V A and Shagaida A A 2009 Hall and ion plasma thrusters for spacecraft (Moscow: Mechanical Engineering)
[5] Sneyd A D and Moffatt H K 1982 J. Fluid Mech. 117 45–70
[6] Magunov A M 2010 Technical Physics 55 991–5