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HEATING OF SOLID MICROPARTICLES IN A PLASMA

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The plasma parameters required to heat solid microparticles (MPs) placed in the plasma to the boiling point of the material at which intensive evaporation occurs have been determined. It is assumed that the vaporized material undergoes ionization, leading to the formation of a secondary plasma comprised of the MP substance. To introduce MPs into the plasma, it is proposed to charge them to a high positive potential outside the plasma and subsequently accelerate them into it using an electrostatic field.

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INTRODUCTION

A common method for producing plasma in a vacuum from a solid-state substance involves evaporating the material from a furnace, followed by ionization [1]. Despite its relative simplicity, this approach has several drawbacks, including inefficient material utilization, contamination of the experimental setup, and environmental concerns due to the potential release of toxic or radioactive elements.

Another method for producing plasma involves the evaporation and ionization of material (typically metals) using a vacuum arc [2]. The advantages of this approach include a high degree of ionization and efficient evaporation of refractory materials. However, one of the main drawbacks is the contamination of both the plasma and the apparatus with microdroplets of material, which reduces the effectiveness of this method, especially when used for coating applications.

A further method of generating plasma from solid-state material involves injecting solid particles into preformed plasma, where they subsequently evaporate and ionize as a result of collisions with plasma electrons and ions. This method is used in fusion devices, where plasma is produced by injecting solid deuterium pellets using a high-velocity injection system [3]. Once in the plasma, the granules evaporate, and the resulting gas is ionized. Based on this concept, we propose introducing MPs of various materials, both metallic and non-metallic, into preformed plasma [4 - 6]. As the MPs enter the plasma, they are heated due to collisions with the plasma's electrons and ions. Under certain conditions, their complete evaporation and subsequent ionization can occur. This approach is more cost-effective and environmentally safe compared to other plasma generation methods and could be particularly useful for producing plasma from rare-earth and radioactive elements.

To introduce MPs into the plasma, it is proposed to charge them to a high positive potential outside the plasma and subsequently accelerate them into it using an electrostatic field. Charging the MPs to a high potential is necessary to impart the maximum possible velocity as well as to maximize its charge, thereby enabling heating through the stored electrostatic energy. This method of accelerating solid MPs with an electrostatic field has previously been employed in laboratory simulations of micrometeoroid flows [7]. Thus the positive charge on the MPs not only facilitates their injection into the plasma but also serves as an additional energy source for heating the MPs.

Alternatively, MPs could be charged to a high negative potential for injection into the plasma, but in this case, the effect of field emission becomes significant, which limits the amount of charge that can be placed on the particle. The positive charge of the particles also has limitations. Specifically, a particle can only be charged up to the emission limit of the ion field of the dust material, which can exceed $E_0 = 10^{10}$ V/m for certain metals. Therefore, the choice of a positive charge for the particles is due to the higher emission limit of the positive field compared to the negative charge.

We developed a model to describe the interaction between a positively charged MP and plasma electrons and ions. In this model, in addition to collisions with electrons and ions, we accounted for secondary electron emission, thermal radiation, the boiling of the particle material upon reaching its boiling point, and other relevant effects. Copper was selected as the material for the particles.

In the initial stage of the model, the MP undergoes recharging due to collisions with plasma electrons, accompanied by heating. In the second stage, once the recharging process concludes, the MP reaches a state with a stationary potential and temperature, determined by the balance of energy flows from collisions with plasma particles, electron emission from the particle, and thermal radiation. The model shows that, depending on plasma parameters the MP temperature can reach the boiling point of the material for a certain period of time. However, the stationary temperature can also be lower than the boiling point due to the processes of energy loss by the particle.

In the present work, we determine the plasma parameters (electron density and temperature) required to establish a steady-state temperature equal to the boiling point of the MP material.

1. MODEL DESCRIPTION

We consider a spherical copper MP with a radius of 1 µm, an initial potential of φ_0 = +10 kV and a temperature of 300 K, which is introduced into a plasma at the initial moment of time. The plasma density n is assumed to be in the range of $10^{10}…10^{12}$ cm^{-3}, the electron temperature T_e ranges from 3 to 100 eV, and the ion temperature T_i is 0.1 eV. The neutral gas pressure is assumed to be approximately 1 Pa.

Upon entering the plasma, the positively charged MP attracts and collects electrons, which leads to its recharging and heating. After recharging, the MP acquires a floating potential and also absorbs plasma ions. The electron and ion currents to the MP surface are given *by:*

$$I_\alpha(\varphi) = e \cdot \Gamma_\alpha ,$$

where $\alpha = i, e$ denote the type of particles, ions and electrons, respectively,

$$\Gamma_\alpha = \sqrt{8\pi} a^2 n v_{T\alpha} \left(1 + \frac{|e\varphi|}{kT_\alpha}\right)$$

is the particle flux in the case of an attractive MP potential and

$$\Gamma_\alpha = \sqrt{8\pi} a^2 n \, v_{T\alpha} \exp\left(-\frac{|e\varphi|}{kT_\alpha}\right)$$

is in the case of a repulsive potential of MP, $v_{T\alpha}$ is the thermal velocity of the particles, a is the radius of the MP, $\varphi = \varphi(t)$ is the MP potential.

The potential and temperature of the MP are also affected by secondary electron emission. The corresponding current is given by

$$I_e^s = \delta I_e ,$$

where the emission coefficient δ is defined as:

$$\delta = \delta_{\max} \frac{|e\varphi|}{E_m} \exp\left(2(1 - \sqrt{\frac{|e\varphi|}{E_m}})\right),$$

with E_m being the energy of primary electrons corresponding to the maximum emission yield δ_{max}.

The time evolution of the MP charge and potential is governed by the current balance:

$$I_i^{pl} - I_e^{pl} + I_e^s = dQ/dt . \quad (1)$$

The temperature evolution of the MP is determined by the net energy flux, including contributions from incoming particles, thermal radiation, and evaporative cooling:

$$P_e + P_i - P_s - P_{th} - P_r - P_{vap} = mc\, dT/dt , \quad (2)$$

where

$P_e = \Gamma_e \cdot (2kT_e + e\varphi + e\Phi)$, $P_i = \Gamma_i \cdot (2kT_i + I + e\Phi)$ are the energy fluxes to the MP from electrons and ions, respectively, I is the recombination energy of the ion, $P_s = \Gamma_s \cdot (\varepsilon_s + e\Phi)$ is the energy flux carried away by secondary electrons, $\Gamma_s = I_e^s / e$, ε_s is the average energy of secondary electrons, $P_r = \sigma T^4$ is the thermal radiation power from the MP surface, σ is the Stefan-Boltzmann constant $P_{vap} = \Gamma_a \cdot (2k_B T + p)$, is the energy loss due to evaporation of the MP material, where

$$\Gamma_a = n' \sqrt{\frac{k_B T}{2\pi m_a}} \exp\left(-\frac{p}{k_B T}\right),$$

with p – the evaporation energy per atom, c is the specific heat capacity of the MP material, m is the mass of the MP.

An important aspect of the model is the choice of the boiling point of the particle material. At atmospheric pressure, the boiling point of copper is approximately 2800 K. As pressure decreases, the boiling point is reduced; the exact value depends on surface properties, evaporation dynamics, and the saturated vapor pressure, as described by the Clausius-Clapeyron equation. At a pressure of approximately 1 Pa, the boiling point of copper is estimated to lie in the range of 1600…1700 K. In this study, we adopt the upper bound of this interval, i.e., 1700 K. It should be noted that at this boiling temperature, the MP does not reach conditions where thermionic electron emission becomes significant. Therefore, this effect is neglected in the present model.

2. DISCHARGE AND HEATING OF MICROPARTICLES

To determine the time dependence of the MP potential and temperature, equations (4) and (5) were solved numerically. The initial potential of the MP was set to φ_0 = +10 kV, corresponding to the upper limit for a particle with a radius of 1 μm. This value is determined by the threshold of ion field emission for the material of the MP, which is estimated to occur at an electric field strength on the order of $E_0 = 10^{10}$ V/m. The temporal behavior of the particle potential in plasmas with varying density and temperature is shown in Figs. 1 and 2, respectively.

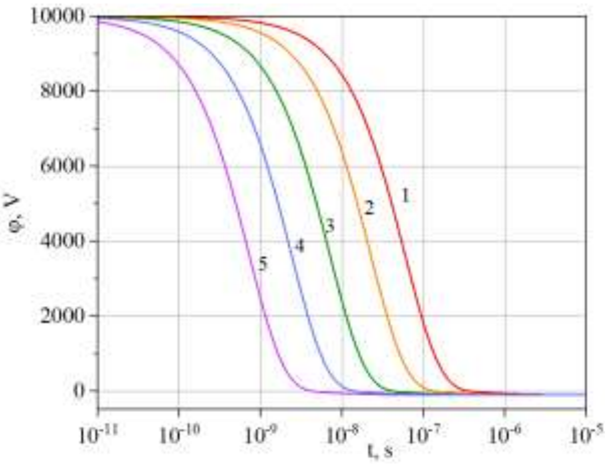

Fig. 1. Time evolution of the MP potential for various plasma densities: 1 – n = 10^{10} cm^{-3}; 2 – n = $3{\cdot}10^{10}$ cm^{-3}; 3 – n = 10^{11} cm^{-3}; 4 – n = $3{\cdot}10^{11}$ cm^{-3}; 5 – n = 10^{12} cm^{-3}; T_e = 30 eV

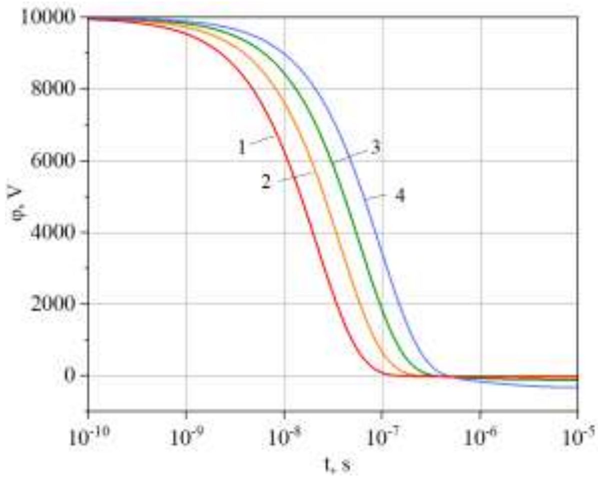

Fig. 2. Time evolution of the MP potential for different electron temperatures: 1 – T_e = 3 eV; 2 – T_e = 10 eV; 3 – T_e = 30 eV; 4 – T_e = 100 eV; n = $3{\cdot}10^{10}$ cm^{-3}

Fig. 1 shows that the MP discharges more rapidly in a higher-density plasma. This is to be expected, as the electron current density incident on the MP is comparatively higher. The discharge time t_d decreases from $t_d = 2\cdot10^{-7}$ s at a plasma density of 10^{10} cm^{-3} to $t_d = 2\cdot10^{-9}$ s at $n = 10^{12}$ cm^{-3}. This indicates that the product $t_d \cdot n$ is approximately constant, with a value of ~ $2\cdot10^3$.

As shown in Fig. 2, the particle discharge time increases with electron temperature from $t = 10^{-7}$ s at $T_e = 3$ eV to $t = 5\cdot10^{-7}$ s at $T_e = 100$ eV. However, the dependence of the discharge time on T_e appears to be relatively weak in this case. Following the discharge, the MP reaches a floating potential determined by the electron temperature.

To estimate the distance from the point of entry into the plasma at which the particle becomes discharged, we consider the velocity of MP with radius r and potential φ, which is approximately given by [6]:

$$v \approx \frac{0.56\varphi_0}{r}, \tag{3}$$

where v is in cm/s, φ_0 is in kV, and r in cm. For $r = 1$ μm and $\varphi_0 = 10$ kV the velocity is $v = 5.6\cdot10^4$ cm/s and the discharge of the MP occurs at a distance of less than 1 mm from the point of plasma entry.

Fig. 3 shows the evolution of the particle temperature over time after its entry into the plasma for different values of plasma density.

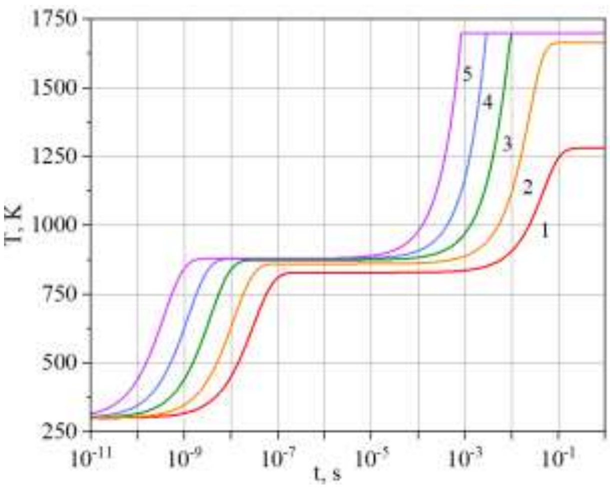

Fig. 3. MP temperature versus time for different plasma densities: 1 – $n = 10^{10}$ cm^{-3}; 2 – $n = 3\cdot10^{10}$ cm^{-3}; 3 – $n = 10^{11}$ cm^{-3}; 4 – $n = 3\cdot10^{11}$ cm^{-3}; 5 – $n = 10^{12}$ cm^{-3}; $T_e = 30$ eV

The figure indicates that heating of MP proceeds in two distinct stages. In the first stage, occurring over a time scale of up to 10^{-7} *s* – corresponding to the discharge duration (see Fig. 1) – the particle is heated by accelerated electrons from the plasma. At this stage, the temperature of the MP reaches approximately 850 K, a value largely independent of the plasma parameters and primarily determined by the electrostatic energy stored in the particle's charge. This amount of energy is insufficient to elevate the particle temperature to its boiling point. In the second stage, the particle acquires a floating potential and is further heated through collisions with plasma electrons and ions. At plasma densities below $n < 3\cdot10^{10}$ cm^{-3} the MP temperature remains below the boiling point (curves 1, 2). However, at higher densities, collisions with plasma electrons and ions lead to additional heating, allowing the particle to reach the boiling temperature (curves 3-5).

According to the data presented in Fig. 3, it can also be observed that the product of the plasma density and the time required to reach a steady-state temperature – at constant electron temperature – remains approximately constant, with a value on the order of 10^9. Extrapolating this relationship beyond the considered range of plasma densities yields, for example, a time of approximately 10^{-5} s for a density of $n = 10^{14}$ cm^{-3}.

Fig. 4 shows the dependence of the MP temperature on time for different electron temperatures at a plasma density of $n = 3\cdot10^{10}$ cm^{-3}.

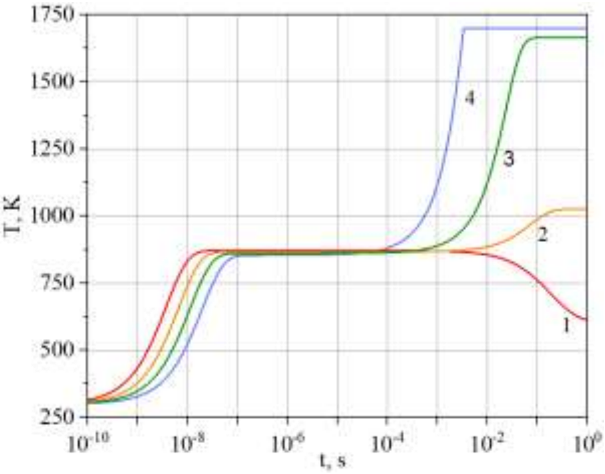

Fig. 4. MP temperature versus time for different electron temperatures: 1 – $T_e = 3$ eV; 2 – $T_e = 10$ eV; 3 – $T_e = 30$ eV; 4 – $T_e = 100$ eV; $n = 3\cdot10^{10}$ cm^{-3}

As seen in the figure, at the second stage of heating there are three distinct regimes of MP temperature behavior. In the first case, at an electron temperature of 3 eV (curve 1), the particle cools down below the temperature reached during recharging, indicating that the energy of electrons and ions is insufficient even to maintain the previously attained temperature. In the second case, at $T_e = 10…30$ eV (curves 2 and 3), the MP continues to heat up, but its temperature does not reach the boiling point of copper. Only in the third case, at T_e=100 eV, does the MP heat up to the boiling temperature.

3. STATIONARY TEMPERATURE OF MP

Figs. 3 and 4 show that, after a certain time following its entry into the plasma, the microparticle temperature reaches a steady-state value T_s. This temperature is determined by the balance between the energy fluxes delivered to the particle through collisions with ions and electrons, and the energy losses due to thermal radiation and emission processes. The steady-state temperature can be determined by solving equations (1) and (2) under stationary conditions, assuming $dQ/dt = dT/dt = 0$, i.e., when the potential and temperature of the MP no longer change. The calculation result is shown in Figs. 5 and 6.

Fig. 5 presents the dependence of the steady-state temperature on plasma density for various electron temperatures. Of particular interest is the plasma density required for the steady-state temperature to reach the boiling point.

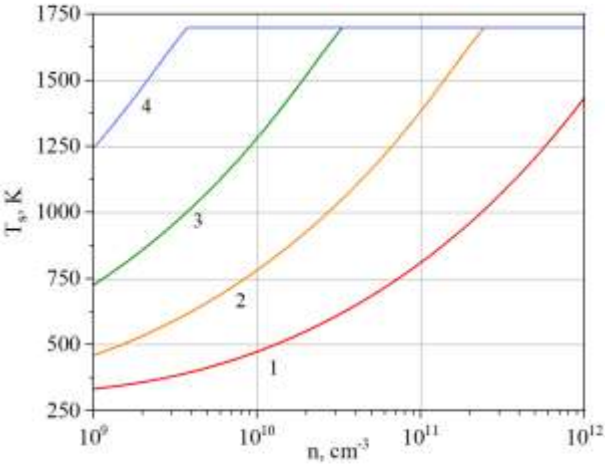

Fig. 5. The stationary temperature of MP versus plasma density at different values of T_e: 1 – T_e = 3 eV; 2 – T_e = 10 eV; 3 – T_e = 30 eV; 4 –T_e = 100 eV

For an electron temperature of 3 eV, the required plasma density exceeds 10^{12} cm^{-3}, whereas for T_e=10 eV and T_e=30 eV, the required densities are approximately $2{\cdot}10^{11}$ and $3{\cdot}10^{10}$ cm^{-3}, respectively. At T_e=100 eV, the boiling point is reached at a plasma density of just $3{\cdot}10^9$ cm^{-3}.

Fig. 6 shows the dependence of the stationary particle temperature T_s on the electron temperature at different plasma density values.

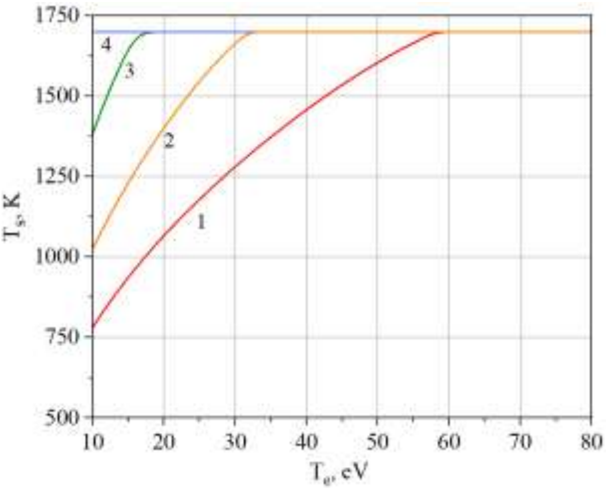

Fig. 6. The stationary temperature of MP versus electron temperature at different values of n: 1 – n= 10^{10} cm^{-3}; 2 –n = $3{\cdot}10^{10}$ cm^{-3}; 3 – n =10^{11} cm^{-3}; 4 – n = $3{\cdot}10^{11}$ cm^{-3}

A steady-state temperature equal to the boiling point of copper is achieved under the following conditions: $n = 10^{10}$ cm^{-3} corresponds to $T_e \approx 58$ eV, $n = 3{\cdot}10^{10}$ cm^{-3} to $T_e \approx 32$ eV and $n_0 = 10^{11}$ cm^{-3} to $T_e \approx 17$ eV.

The data shown in Figs. 5 and 6 allow for the estimation of the plasma density and electron temperature required for the MP material to reach its boiling point:

$$nT_e^2 \geq 3{\cdot}10^{13},$$

where n is in cm^{-3} and T_e is in eV. Extrapolating this result beyond the considered plasma density range yields, for instance, the condition $T_e > 0.5$ eV at a density of $n = 10^{14}$ cm^{-3}. Likewise, for an electron temperature of 1000 eV, the corresponding condition for the plasma density is $n > 10^7$ cm^{-3}.

Let us estimate the distance l from the point of particle injection into the plasma at which the particle reaches its boiling point. At T_e = 30 eV, the particle boiling time is $10^{-3}…10^{-2}$ s depending on the plasma density (see Fig. 3). Considering that the particle velocity, obtained from (3), is $v = 5.6{\cdot}10^4$ cm/s, we obtain l ~ 60…600 cm.

CONCLUSIONS

An evaluation of the feasibility of heating a solid MP to its boiling point upon entering a plasma has been performed. To inject the particle into the plasma, it is proposed to pre-charge it with a positive charge φ_0 = +10 kV and accelerate it by means of an electrostatic field. The scenario considered assumes that the particle is charged to the maximum possible positive potential, limited by the ion field emission threshold of the particle material.

It has been established that, after entering the plasma, the MP discharges over a time t_d, which is related to the plasma density by the approximate relation $t_d{\cdot}n \sim 2{\cdot}10^3$. The dependence of the discharge time on the electron temperature is relatively weak, showing a slight increase with increasing T_e. During the discharge to the floating potential, the particle travels less than 1 mm, heating up through collisions with electrons due to the stored electrostatic energy and reaching a temperature of approximately 850 K. This indicates that the stored energy is insufficient to raise the particle temperature to the boiling point. Subsequent heating occurs under floating potential conditions, leading to the establishment of a steady-state temperature determined by the balance between incoming and outgoing energy fluxes.

It is shown that the particle temperature reaches the boiling point when the condition $nT_e^2 \geq 3{\cdot}10^{13}$ is satisfied, where n is expressed in cm^{-3} and T_e in eV. The distance at which boiling occurs is estimated to range from 60 to 600 cm, depending on the specific plasma conditions. These findings indicate that complete evaporation of a MP of moderate size under the described injection conditions is not feasible.

One possible approach to overcoming these limitations is to lower the charging voltage of the MP, which will result in a reduced injection velocity into the plasma. However, if a high MP velocity is necessary – for instance, to control the distribution function of the resulting ions – the heating rate of the MP may be enhanced by introducing a high-energy electron beam [6, 8]. Alternatively, the plasma density can also be increased, for example, through the use of a pulsed reflex discharge [9].

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НАГРІВ ТВЕРДИХ МІКРОЧАСТИНОК У ПЛАЗМІ

Д.В. Чібісов, О.Д. Чібісов

Визначено параметри плазми, необхідні для нагрівання твердих мікрочастинок (МЧ), розміщених у плазмі, до температури кипіння матеріалу, за якої відбувається інтенсивне випаровування. Вважається, що отримана пара зазнає іонізації, утворюючи плазму, що складається з речовини МЧ. Для введення МЧ у плазму пропонується спочатку зарядити їх до високого позитивного потенціалу поза плазмою, а потім прискорювати у плазмі за допомогою електростатичного поля.