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Simulation of dust grain charging under tokamak plasma conditions

Zhuang Liu[a,b,*], Dezhen Wang[b], Gennady Miloshevsky[a]

[a] Center for Materials under Extreme Environment, School of Nuclear Engineering, Purdue University, West Lafayette, IN 47907, USA
[b] Key Laboratory of Materials Modification by Laser, Ion and Electron Beams (Ministry of Education), School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, People's Republic of China

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ABSTRACT

Dust grains in fusion devices may be radioactive, contain toxic substances, and may penetrate into the core plasma resulting in the termination of plasma discharges. Therefore, it is important to study the charging mechanisms of dust grains under tokamak's plasma conditions. In this paper, the charging processes of carbon dust grains in fusion plasmas are investigated using the developed dust simulation (DS) code. The Orbital Motion Limited (OML) theory, which is a common tool when solving dust-charging problems, is used to study the charging of dust grains due to the collection of plasma ions and electrons. The secondary electron emission (SEE) and thermionic electron emission (TEE) are also considered in the developed model. The surface temperature of dust grains (T_d) is estimated for different plasma parameters. Floating potentials have been validated against the data available from the dust simulation code package DUSTT. It is shown that the dust grains are negatively charged for relatively low plasma temperatures below 10 eV and plasma densities below 10^{19} m^{-3}. For higher plasma temperature and density, however, the charge on dust grains may become positive. The charging time depends not only on the grain's size, but also on the plasma temperature.

1. Introduction

In fusion devices, the majority of the plasma escaped from the core and directed towards the divertor moves along the scrape-off layer, where plasma recombination occurs and most of the contamination is exhausted. Small portion of escaped hot plasma, however, fails to move along the magnetic lines and hits the chamber wall and the dome area [1,2]. The chamber wall or dome produces eroded material when being hit by the plasma. The eroded material may nucleate and form dust grains in relatively cold plasma regions [3]. Consequent flaking of the thin surface films, which are produced during the interaction between the plasma and chamber wall, as well as other plasma-wall interactions, are also sources of dust grains [4]. Some dust grains are radioactive and toxic, some contribute to the plasma contamination as a supplier of impurity, some could result in radiative losses, plasma instabilities and even the termination of plasma discharges when they penetrate into the core plasma [5,6].

The physical processes of charging of dust grain have been studied in various fields [7–11]. Tokamak operation and safety issue due to contamination by dust grains, intentionally injected (Li pellets) or produced during energetic plasma-wall interactions, is among the most critical issues to deal with in magnetic fusion devices. Since the dust grains could be charged, they can be located in various places in a tokamak. Most of the grain sizes are found on the order of 0.1 μm to 10 μm [12]. Some of the grains are spherical and some can be of irregular shape [13]. There are mainly four dust simulation code packages in magnetic fusion research, namely DUSTT [14], DTOKS [15], MIGRAINe [16] and DUSTTRACK [17] . All the four codes give a description of dust behavior and transport in fusion devices. The DS code, however, focuses on the dynamic charging processes as well as the influences of background plasma parameters and the dust grain property.

In this paper, to have direct and simple expressions for the currents, we consider spherical dust grains originating from the sputtering yields of the plasma facing material. The charging mechanisms of dust grains with different sizes in fusion plasma environments are studied. By means of our Dust Simulation (DS) code based on the experiments [12,18] of dust formation and basic plasma parameters in fusion devices, the T_d evolution and charging processes of dust grains are studied. The developed code was also used to provide a theoretical basis for understanding dust contamination of the core plasma and optimization of the tokamak

* Corresponding author.
E-mail address: lzplasma@mail.dlut.edu.cn (Z. Liu).

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vessel wall. Calculations with the DS code have been performed for various sizes of spherical dust grains with common edge plasma parameters. For most of the edge plasma conditions the results show that the charge on grains remains negative. Under relatively higher temperatures above 10 eV, however, the TEE becomes strong enough to turn the grain's charge to positive values.

The paper is organized as follows. In Section 2, the dust-charging model is presented. In Section 3, the charging processes of carbon and tungsten dust particles with various sizes are studied in detail and the conclusions are drawn in Section 4.

2. Physical model

2.1. Dust charging due to interactions of plasma electrons and ions

Dust charging is the result of dynamic processes of ions and electrons reaching, interacting, and leaving the surface of dust grains. The processes that contribute to dust grain charging are collection of electrons and ions from the plasma, secondary emission, thermionic emission, photoemission, and radioactivity [3]. Since the influences of the last two processes are relatively small and can be neglected [19], our DS code accounts for collection of charged particles from the plasma, secondary emission, and TEE. In our simulations, we assume that the dust grains are spherical and the plasma particle motion is gyro-centered. The dynamic charging process is described with the OML [20], which was originally used for calculating the charge on a probe immersed in the plasma [21]. For typical edge fusion plasma parameters, Te ranging from 1 eV to several tens eV and Ne ranging from 10^{18} m^{-3} to 10^{20} m^{-3} [19], the electron and ion collisions can be safely neglected in calculations of dust charging and heating [14]. For ions, the Larmor radius is much larger than the Debye screening length, which is also larger than the grain radius (from 1 to 10 µm), so that the OML approximation can be used [3]. For electrons, the Larmor radius is comparable with the Debye length. The effect of the magnetic field on dust grain charging will be considered in the future work. For Maxwellian distributed electrons and ions, characterized by temperature of electrons T_e and ions T_i, which are equal in thermal equilibrium, the OML currents for spherical grains can be written as [22]

$$\begin{aligned} I_i &= I_{oi}\left(1-\frac{z_i e\varphi_s}{k_B T_i}\right) && \varphi_s<0\\ I_e &= I_{oe}\exp\left(\frac{e\varphi_s}{k_B T_e}\right) && \varphi_s<0\\ I_i &= I_{oi}\exp\left(\frac{-z_i e\varphi_s}{k_B T_i}\right) && \varphi_s>0\\ I_e &= I_{oe}\left(1+\frac{e\varphi_s}{k_B T_e}\right) && \varphi_s>0 \end{aligned} \tag{1}$$

where z_i is the ion charge, I_{oe} and I_{oi} are the currents when the grain's surface potential $\varphi_s = 0$, e is the elementary charge and k_B is the Boltzmann constant. The terms $I_{o\alpha}$ with $\alpha = e, i$ can be written in the simplified form

$$I_{o\alpha} = 4\pi R_d^2 N_\alpha q_\alpha \left(\frac{kT_\alpha}{2\pi m_\alpha}\right)^{1/2} \tag{2}$$

under tokamak plasma edge conditions, where R_d is the dust radius, N_α is the number density, q_α is the charge number, and m_α is the mass of plasma species α, respectively. The dust grain surface potential φ_s is related to the dust charge Q as

$$\varphi_s = Q/C \tag{3}$$

where C is the capacitance of a spherical dust grain which has the form $C = 4\pi\varepsilon_0 R_d$ [23]. The charging process due to plasma ions and electrons can be described as

$$\frac{dQ}{dt} = I_i + I_e \tag{4}$$

Substituting Eq. (3) into Eq. (1) and using Eqs. (2) and (4) we obtain

$$\begin{aligned} \frac{dQ}{dt} &= 4\pi R_d^2 N_e q_e \left(\frac{kT_e}{2\pi m_e}\right)^{1/2} \exp\left(\frac{eQ}{kCT_e}\right)\\ &\quad + 4\pi R_d^2 N_i q_i \left(\frac{kT_i}{2\pi m_i}\right)^{1/2}\left(1-\frac{z_i eQ}{kCT_e}\right) \quad \varphi_s<0 \end{aligned} \tag{5}$$

$$\begin{aligned} \frac{dQ}{dt} &= 4\pi R_d^2 N_e q_e \left(\frac{kT_e}{2\pi m_e}\right)^{\frac{1}{2}} \left(1+\frac{eQ}{kCT_e}\right)\\ &\quad + 4\pi R_d^2 N_i q_i \left(\frac{kT_i}{2\pi m_i}\right)^{1/2}\exp\left(\frac{-z_i eQ}{kCT_i}\right) \quad \varphi_s>0 \end{aligned} \tag{5}$$

These equations describe the charge evolution due to collection of plasma electrons and ions for various plasma temperature and density conditions.

2.2. Secondary electron emission (SEE)

With sufficient energy of plasma electrons hitting the dust grains, electrons can be ejected from the dust grain. The SEE yield, the ratio of the emitted secondary electrons to the whole incoming electrons, is affected by the energy of incoming electrons E_e and is described by the Sternglass formula [24]

$$\frac{\delta_{sec}}{\delta_{max}} = 2.72^2 \frac{E_e}{E_{max}} \exp\left[-2\left(\frac{E_e}{E_{max}}\right)^{1/2}\right] \tag{6}$$

where δ_{max} and E_{max} are material-dependent constants and δ_{sec} is the SEE coefficient. For graphite, $\delta_{max} = 1.0$ and $E_{max} = 300$ eV [25]. Then we can integrate numerically δ_{sec} over the energy distribution of electrons $E_e = \frac{1}{2} m_e v_e^2$ using a Maxwellian distribution function $f(E_e, T_e)$ to determine SEE as a function of temperature T_e [26]. For positively charged grains, the SEE contribution is neglected, since it is assumed that the grain is sufficiently charged to absorb the secondary electron current. The SEE can also be obtained from Young-Dekker formula [27]. Its incorporation in the code and comparison to the Sternglass formula will be done in the future work.

2.3. Thermionic emission

2.3.1. Thermionic current

When T_d is high enough, some electrons can escape resulting in thermionic emission. The thermionic current for negatively charged grains with the radius of R_d can be obtained using the Richardson-Dushman equation [28]

$$j_{th} = -4\pi R_d^2 A_R T_d^2 \exp\left(-\frac{W_f}{k_B T_e}\right. \tag{7}$$

where $A_R = 1.20173 \times 10^6\ A\ m^{-2}\ K^{-2}$ is Richardson's constant, W_f is the material-dependent work function. For graphite, $W_f = 4.8$ eV [26]. For positively charged grains, just as SEE, this thermionic term is also neglected.

2.3.2. Surface temperature of dust grains T_d

There are five main heating and cooling mechanisms contributing to the net energy on dust grains in a fusion plasma [26]. These are particle bombardment, electron emission, recombination processes, neutral particle emission, and radiative cooling. For