氏　　　名	Smirnov,Roman
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論文審査委員	主　査　教授　林　隆也 助教授　冨田　幸博 教授　室賀　健夫 教授　石原　修（横浜国立大学） 助教授　滝塚　知典（日本原子力研究所） 助教授　大野　哲靖（名古屋大学）

論文内容の要旨

In present fusion devices the generation of dust particles is observed and characteristics of the dust particles collected after discharges have been analyzed. Typically the collected dust particles have irregular, flake or spherical shapes with sizes from nanometers to tens of micrometers and consist of materials of divertor plates, first wall or inner structures. They are considered to appear in a plasma due to erosion of plasma-facing surfaces, condensation and adhesion of plasma-spattered materials, flaking of redeposition layers. The motion and destruction of dust particles in the high temperature plasma region can contribute to the impurity transport that makes essential to study behavior of dust particles during a discharge. It is well known that dust particles obtain large, usually negative, electrical charge (up to 10^6 elementary charges) in a plasma and can affect electric potential distributions and change kinetic properties of the plasma due to scattering and absorption of plasma particles. The important safety issue is the ability of dust particles to accumulate large amount of radioactive tritium. The dust may be a primary radiological and explosion risk factor. In recent years dust particles also have attracted attention in growing technological applications of plasmas connected to astrophysical, space, laboratory, and processing applications. In fusion devices the dust density usually is not high enough to show the collective effects. Therefore, the aim of the present study is to investigate the behavior of a single dust particle in a plasma wall transition layer that includes sheath formation with the dust particle, analysis of releasing conditions at the wall and possible trajectories of dust particles with various sizes and masses. We consider a conductive spherical dust particle initially placed on the wall. The directions and magnitudes of the forces acting on the dust depend on the local plasma parameters, dust particle size and charge. The present problem needs to be analyzed self-consistently because the charge of the dust particle affects the surrounding plasma and mutually depends on fluxes of electrons and ions to the dust particle. This presents significant difficulties in the theoretical treatment of such problem; therefore, we used computer simulations in combination with a simplified theoretical approach. Assuming local plasma parameters known and fixed we can theoretically find the charge, currents and forces to the dust particle that allows to analyze its behavior in a wide range of sizes, masses, spatial and time scales.

At first, we investigate the conditions allowing a dust particle to be released from the wall, when the total force is acting on the dust towards plasma. The total force in our analysis includes the electrostatic force, the drag forces due to ion absorption and scattering, the electrostatic image force due to redistribution of charges on the wall and the gravitational force. The ion drag force is obtained using the Orbital Motion Limited (OML) theory, which gives us absorption cross section of electrons and ions by the dust particle, and the charge of dust particle attached to the wall is determined by the wall surface charge density and dust radius. The condition for releasing of the dust particle is obtained analytically in respect to the dust radius. From this condition we derive the "first critical dust radius" that is the largest radius of the dust particle capable to leave the wall. Using estimations of plasma parameters near the wall according to the Bohm sheath theory, we can express the first critical radius as a function of the wall potential.

For the case of the zero gravitational force (vertical surfaces), it was shown that the first critical radius exists only when the wall potential exceeds the threshold value, below which no dust particles can be released from the wall. For the deeper wall potentials than the threshold one, the smaller dust particle than the first critical radius will be released and the bigger one will be pinned to the wall due to the large ion drug force compared to the electrostatic force. Changing the wall potential we can control the size of released dust particles or suppress motion of all dust particles. When the gravitational force is directed toward the wall, it reduces the value of the first critical radius, but does not affect the threshold potential. For the opposite direction of the gravitational force, there are two values for the first critical radius, which define two zones in the "dust radius – wall potential" space for the released dust particles. Configuration of the zones is controlled by the gravitational parameter that is a function of dust mass density and plasma parameters. One of the zones is dominated by the electrostatic force and another one by the gravitational force. For a large gravitational parameter they are merged, while for a small one they are separated by a range of wall potentials, where no dust particles can leave the wall.

The motion of the released dust particles in one-dimensional (1D) boundary plasma is analyzed numerically by solving dust motion and charging equations simultaneously. In the model of a plasma being not affected by the dust particle, we consider the 1D system bounded at one side by a perfectly absorbing electrically biased wall and at another side bordering with a bulk plasma with given densities and temperatures of electrons and ions. The bulk plasma provides continuous inflow of plasma particles into the system, which is filled with uniformly distributed neutral gas. A Debye sheath is formed in front of the wall and an extended ionizing presheath is formed further from the wall due to electron impact ionization of neutral atoms. This system was simulated with the originally developed 1D Particle-in-Cell/Monte-Carlo (PIC/MC) code. The simulations conducted to achieving the steady state give us the spatial distributions of plasma parameters (densities, flow velocities, temperatures, potential etc.) in the sheath and the presheath. Using the OML theory and simulated plasma parameters, we found currents and forces to the dust particle and solved dust dynamics equation numerically. The simulated trajectories of the released particles in a plasma show small or large amplitude oscillations that are sharply discriminated with the critical radius: the “second critical radius”. The smaller dust particles than the second critical radius have a large amplitude of oscillations going deeper into the plasma. The existence of the second critical radius is caused by the appearance of an effective potential barrier near the wall due to reduction of the dust charge that depends on sharply changing local plasma parameters. The second critical radius is increasing with decreasing of the dust mass due to a delayed charging effect. This effect leads to the dust charge is being larger than the local equilibrium one during the motion of a released particle from the wall, thus allowing the lighter dust particles to oscillate with a larger amplitude. When the dust mass is smaller than a certain critical value, there is no more clear discrimination between small and large amplitude oscillations and the second critical radius disappears.

The 1D model applied here does not take into account effects of interaction between a dust particle and a plasma. When the size of dust particle is larger than the Debye length, these effects may be significant and disturb the wall sheath formation around the dust particle. For the self-consistent analysis of the spherical dust particle behavior in a boundary plasma near the wall, the two-dimensional (2D) PIC simulations with a cylindrical symmetry are carried out. The charge, electron and ion currents and forces are simulated for a dust particle attached to the wall. It is shown that the simulated dust charge is in a good agreement with the theoretically calculated one for the smaller dust size than the Debye length. The theoretical value is calculated for a polarized dust particle at the wall in non-uniform external electric field, where the interaction between dust and plasma is not included. When the dust size is larger than the Debye length, the absolute value of the dust charge is significantly higher than the theoretical value. This result is explained by the enhanced normal electric field at the dust surface due to the plasma shielding effect. This effect also leads to increasing of the repulsive electrostatic force and the first critical radius. Simulation result of the electron current density to the dust particle shows weak dependence on the dust size contrary to the OML prediction. A modified OML expression for the electron current density was presented, where the surface potential of the dust is replaced by the fixed wall potential. This modification shows good agreement with the simulation results. The same substitution for the ion current density also eliminates its dependence on the dust particle radius; nevertheless, the discrepancy exists between the simulation results and the modified OML formula. Further modification of the OML expression was made by taking into account the sharp change of the impact parameters (potential energy and flow velocity) of absorbed ions inside the sheath. This correction gives a good agreement between simulation results and theory for the smaller dust particles. For the dust particles bigger than the sheath width, the saturation of the ion current density was observed due to the development of the individual spherical sheath around the dust particle. The 2D simulations confirmed the existence of the first critical dust radius and showed good agreement with the prediction by the 1D model for the smaller dust particles than the Debye length.

In this study the existence of the first critical dust radius was predicted theoretically and confirmed with the 2D self-consistent simulations. We found the second critical dust radius separating small and large amplitude oscillations of the dust particles in the boundary plasma. The 2D self-consistent simulations of a dust particle on the wall gave us a good agreement with the theoretical results for the smaller dust than the Debye length and showed enhancing effect of the dust sheath on the dust particle charge and the electrostatic force. Modifications of the OML expressions for electron and ion current densities are proposed. The self-consistent simulations of the dust particle dynamics in the sheath as well as effects of a magnetic field and various elementary processes remain of the future issues. The results of this research give us the principle understanding of the dust characteristics in boundary plasmas and can contribute to the investigation of the dust dynamics in the realistic and complex situations.

論文の審査結果の要旨

近年、核融合プラズマ実験装置［LHD（日）、TEXTOR-94, ASDEX-U（独）、等］で数千放電の後、装置内壁の微粒子（ダスト粒子）の収集、観測が行われている。これらの微粒子はダイバータ板やプラズマ周辺金属壁等から発生して、大きさは数十ナノｍ から 数百ミクロン程度におよび、形は球状やフレーク状と様々で、その成分は構造材料の金属や炭化水素から成っている。今後、プラズマ保持時間の長時間化に伴い、これらの微粒子の発生は顕著になると思われる。発生した微粒子は通常負に帯電（素電荷の 10^3—10^5 倍）しており、閉じ込めプラズマに対しては不純物となってプラズマ閉じ込めの性能を悪化させる可能性がある。さらに、将来、重水素及び三重水素を燃料にした核融合炉では、これらの微粒子が放射性同位元素である三重水素を多量に吸収し、放電終了後の微粒子の扱いや回収等は、安全性の観点から国際熱核融合実験炉 ITER においても解決すべき重要な課題の一つに挙げられている。これまで、微粒子に関しては宇宙、実験室プラズマ中の集団的振る舞い（組織化、不安定性）の研究が流体モデルを用いて行われてきた。本研究では、これまでの研究に考慮されていない金属壁の存在や、プラズマと金属壁との境界層プラズマ領域での非一様電界等の効果を取り入れて、微粒子の振る舞いの解明を目的としている。ここでは、微粒子を個別粒子として扱っているが、核融合プラズマ中での微粒子密度は集団現象が問題となるほど高くないために、妥当と思われる。

本研究では最初に、一次元理論解析によって微粒子の壁からの離脱条件を求めている。そこでは、静電力、プラズマイオン吸収による力、プラズマとの摩擦力、鏡像力、さらに重力の効果が取り入れられ、その結果以下の新発見が得られた。

1）微粒子が壁から離れるために壁電位に閾値が存在する。

2）閾値以上の深い壁電位の場合に、離脱する微粒子の大きさに最大値が存在する。さらに、壁から離れる方向に重力が働く場合に、閾値以下の浅い壁電位でも、重力の効果によって、離脱する微粒子が存在する。

3）以上の結果から、壁電位を調節することによって壁から離脱する微粒子の大きさや質量をコントロールできる可能性が示された。

次に、壁から離脱した微粒子のプラズマ・壁境界層での挙動を調べるために一次元粒子シミュレーションコードが新規に開発された。このコードの正当性は理論と比較して確かめられている。その結果、以下の新事実を発見した。

1）大きな微粒子は壁前面に形成された電位の丘のためにプラズマ中へ浸透できない。

2）この電位の丘の形成には、微粒子の運動と帯電時間の関係より微粒子質量に閾値が存在して、これより軽い微粒子はプラズマ中深く進入可能である。

さらに、大きさがデバイ長以上の微粒子の挙動を調べるために軸対称二次元粒子シミュレーションコードが新たに開発された。その結果、以下の成果が得られた。

1）プラズマ粒子の微粒子への吸収に関するこれまでの理論モデルは、半径がデバイ長以下では有効であることが明らかになった。その結果、一次元モデルで推測された離脱微粒子半径の最大値が二次元シミュレーションによって確認された。

2）壁上のデバイ長以上の微粒子への吸収電流の理論モデルに修正が提案された。

以上の成果は、核融合プラズマのみならず、プロセスプラズマや実験室プラズマ中での

微粒子の抑制や挙動解析に重要な知見を与えている。今後、磁界や種々の形状、材質の微粒子を考慮することにより、本分野の研究発展にさらに貢献すると考えられる。これらにより、学位論文として十分な価値がある内容を含むと判断した。