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Analysis of Pellet Ablation

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Abstract

In order to construct a new ablation model including a realistic equation of state of hydrogen and atomic process, the fluid equations consisting of neutral atoms, ions and electrons are calculated in an ablation cloud. In result, the ablation rate is reduced to about half value of one of Parks model, in a bulk plasma with electron temperature of 6.5 keV and density of 3.2×10^{21} m^{-3}, because of ionization of the atoms.

Keywords:
pellet, ablation, equation of state

1. Introduction

Refueling is one of essential methods in order to control plasma density and sustain steady state plasmas. A gas puffing has been successful in building and sustaining a plasma density in an experimental system of past generation. However, in a large scale experimental system, e.g., LHD, the plasma sources induced by the gas puffing are strongly localized near the plasma surface. Then, a pellet injection is placed as a fundamental tool and has been mainly used to obtain a high density plasma and control a density profile [1].

A theoretical analysis of the pellet injection was started by Rose [2], and several ablation models for the pellet based on different physics were developed, e.g., a neutral gas shielding model set up by Parks and Turnbull [3]. However, in the ablation models, it is assumed that the pellet is an ideal fluid without atomic processes, e.g., ionization and recombination. Then, we will develop a new ablation model including these effects. Our final goal is to investigate the bulk plasma motion induced by the pellet injection including pellet dynamics, by developing a three dimensional fluid code with a neutral fluid and MHD plasma. The work is its first step that will give the prospect of physics in the simulation.

When a pellet consisting of solid hydrogen is heated by an energy flux, it changes to liquid and vapor during phase transition and subsequently to plasma during atomic process. In general, the states of solid, liquid and vapor are dominated by the equation of state (EOS) [4]. Then, the phase transition is treated by determining pressure and internal energy as functions of density and temperature with the EOS. Ionization and recombination can be introduced as source terms into mass and energy conservation equations. In the present work, the ablation cloud consists of three species fluids, namely, neutral atoms, ions and electrons. These species have different temperatures and a same velocity on the assumption that the charge neutrality and strong charge exchange lie in the ablation cloud except for incident plasma electrons encountering the cloud. In result, we obtain a new ablation rate including the effects of the EOS and ionization and recombination. In order to clarify the difference between the new model and conventional model [3], the ablation rate is evaluated in the bulk plasmas with high energy, because the heat flux from the bulk plasma with higher energy can reach more

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dense region in the ablation cloud that is dominated by the realistic EOS instead of the ideal EOS.

2. Basic Equations

All species evolved are assumed to be treated as fluids, though there is some doubt as to the validity of this assumption in the bulk plasma. Since the ablation cloud has a very high density and low temperature, it has a high collision rate required for the validity of a fluid treatment. The hot bulk plasma, which is not accurately treated as a fluid, has a minimal effect on the ablation process, except for an effect as the source for the heat flux which drives the ablation (and which is calculated kinetically). Incident plasma electrons encountering the ablation cloud of the pellet lose energy through inelastic processes such as ionization and excitation of the neutral hydrogen molecules and/or atoms and simultaneously undergo elastic scattering. Both effects degrade the total incident electron energy flux providing a energy source to expand the ablation cloud. Assuming that Maxwell Boltzmann statistics apply to the plasma electrons far away from the pellet which have temperature T_∞ and density n_∞, the electron energy flux prior to interaction with the pellet is given by:

$$q_\infty = n_\infty v_\infty E_\infty / 4 \tag{1}$$

where $v_\infty = \sqrt{8KT_\infty/(\pi m_e)}$, $E_\infty = 2kT_\infty$, m_e is the electron mass, and k is the Boltzmann constant.

As an approximation, the distribution of electrons is replaced with an equivalent mono-energetic flux of electrons with the average energy, E. Assuming that these mono-energetic electrons lose their energy continuously as they enter the ablation cloud, a relation between energy, E, and distance, r, of an electron traveling along the magnetic field line is given by:

$$\frac{\mathrm{d}E}{\mathrm{d}r} = \frac{2\rho L(E)}{m\langle\cos\theta\rangle} \tag{2}$$

where ρ and m are the mass density and average mass in the ablation cloud, respectively, and $L(E)$ is the energy dependent loss function. The $\langle\cos\theta\rangle$ term accounts for the average pitch angle of the electrons with respect to the magnetic field line which is approximated by 1/2 if it is weighted with an isotropic distribution. In the mono-energetic approximation, the equation governing the incident electron energy flux, q, at a point, r, in the ablation cloud is:

$$q(r) = q_\infty \frac{E(r)}{E_\infty} \exp\left[\int_{E_\infty}^{E(r)} \frac{\sigma_{\mathrm{T}}(E')}{2L(E')} dE'\right], \tag{3}$$

where σ_T is the effective backscattering cross section which includes small angle scattering as well as single event backscattering. Expressions of $L(E)$ and $\sigma_T(E)$ are described in Ref. [3].

The dynamics of the ablation cloud are given by the equations of mass, momentum and energy conservations including the electron heat flux, q. The cloud is assumed to consist of atoms, ions and electrons and be in a spherically symmetric expansion. In addition, the ions and electrons have a same velocity, u, due to assumption of charge neutrality, and the atoms and ions have the same velocity, u, and the same temperature, T_h, due to assumption of strong charge exchange. An electromagnetic force is ignored for simplicity that will be discussed in a later paper. In result, we obtain the following equations:

$$\frac{\mathrm{d}}{\mathrm{d}r}(\rho_s u r^2) = S_s \tag{4}$$

$$\sum_{s=n,i,e} \rho_s u \frac{\mathrm{d}u}{\mathrm{d}r} = -\frac{\mathrm{d}}{\mathrm{d}r}\left(\sum_{s=n,i,e} p_s\right) \tag{5}$$

$$\sum_{s=n,i} \rho_s C_{\mathrm{V}_s} u \frac{\mathrm{d}T_h}{\mathrm{d}r} = -\frac{\Sigma_{s=n,i} P_{\mathrm{TH}s}}{r^2} \frac{\mathrm{d}}{\mathrm{d}r}(r^2 u) + Q_h - \sum_{s=n,i} S_s\left(\varepsilon_s - \frac{1}{2}u^2\right) \tag{6}$$

$$\rho_e C_{\mathrm{V}_e} u \frac{\mathrm{d}T_e}{\mathrm{d}r} = -\frac{P_{\mathrm{TH}e}}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}(r^2 u) + Q_e - S_e\left(\varepsilon_e - \frac{1}{2}u^2\right) \tag{7}$$

where ρ is the density, u the velocity, p the pressure, ε the specific internal energy, S the particle source and Q the heat source. C_{V} is the specific heat for constant volume, and P_{TH} is the effective pressure that is reduced to the conventional pressure in an ideal gas. These thermodynamic variables are mentioned later. The subscripts n, i, e and h denote the values of atom, ion, electron and heavy particle (atom and ion), respectively. S is given by the following equations:

$$S_n = m_n(Rn_i n_e - In_n n_e) \tag{8}$$

$$S_i = m_i(In_n n_e - Rn_i n_e) \tag{9}$$

$$S_e = m_e(In_n n_e - Rn_i n_e) \tag{10}$$

where R and I are the recombination and ionization coefficients, respectively. Q is given by:

$$Q_h = Q_n + Q_i = \nu_{eh}(T_e - T_h) + H_h \qquad (11)$$

$$Q_e = \nu_{eh}(T_h - T_e) + H_e - \frac{S_e}{m_e}\varepsilon_{\text{ion}} \qquad (12)$$

$$H = K\frac{\mathrm{d}q}{\mathrm{d}r} = K\, n_h q \Lambda(E) = H_h + H_e \qquad (13)$$

where ν_{eh} represents the collisional energy exchange between the electrons and heavy particles. ε_{ion} is the ionization energy of hydrogen that is 13.6 eV. H_h and H_e represent heating of the heavy particles and electrons due to the incident electron encountering the ablation cloud. $\Lambda(E) = \sigma_T(E) + 2L(E)/E$, that is derived by Eqs. (2) and (3), can be regarded as an effective energy flux cross section. The local heating rate, H, is simply given by dq/dr. K is the fraction of the electron energy loss and is approximately 0.6–0.7 [5] that is assumed to be a constant at all points in the cloud for simplicity. In partially ionized ablation cloud, most of this energy is deposited in the electrons, though some of it appears as kinetic energy of collisionally ionized ions. Then, it is assumed that $H_h = 0.2H$ and $H_e = 0.8H$.

The thermodynamic variables have the following relation:

$$\mathrm{d}p_s = c_s^2\, \mathrm{d}\rho_s + \frac{P_{\mathrm{TH}s}}{T_s}\, dT_s \qquad (14)$$

where $C_{V_s} = \partial\varepsilon_s/\partial T_s|_\rho$, $c_s^2 = \partial p_s/\partial\rho_s|_T$, and $P_{\mathrm{TH}s} = T_s\partial p_s/\partial T_s|_\rho$. These variables are solved by using the EOS. The realistic EOS for hydrogen evaluated by More [4] is used in the paper. In the conventional ablation models, the EOS for an ideal gas is used.

As boundary conditions necessary to determine the solution, it is assumed that a shock is free, and the electron energy, E, and energy flux, q, must approach those of the bulk plasma (E_∞ and q_∞) as $r \to \infty$. At the pellet surface, a density and temperature are 0.1 g/cm^3 and 0.01 eV, respectively, that approximately mean parameters of the solid hydrogen. The heat flux is assumed to be so strong as to arrive around the pellet surface.

3. Ablation Rate

In this section, the special structures of the ablation are shown by solving Eqs. (4)–(7) for various boundary conditions and the resultant ablation rates are compared with ones from a conventional ablation model. Figure 1(a) shows normalized density, n/n_p, as a function of normalized radius, r/r_p. r_p and n_p are the pellet radius (r_p = 1 mm) and atom density (corresponding to 0.1 g/cm^3) at the pellet surface, respectively. A solid, dashed and dot-dashed lines express the atom density profiles for T_∞ = 77 keV and $n_\infty = 1.0 \times 10^{19}$ m^{-3} (case 1), 19 keV and 4.9×10^{19} m^{-3} (case 2), and 6.5 keV and 3.2×10^{21} m^{-3} (case 3), respectively. The density decreases in any cases in the radius direction because of expansion induced by the heat flux. In the case 1, the electron has the highest temperature and the lowest density. Then, the ablation rate is highest and the expansion velocity is largest, and so the density distribution is reduced to a broad profile. In the case 3, the electron has the lowest temperature and the highest density. The density distribution is fairly narrower than one for the case 1. Figure 1(b) shows the density profile that is different from Fig. 1(a) on the scale of x- and y-axes. The definitions of lines are the same as Fig. 1(a). A thin solid, dashed and dot-dashed lines show the ion densities in the cases 1, 2 and 3, respectively. In the case 3, the ion density increases and becomes greater than the atom density in the radius direction, because some atoms are ionized by the heat flux from the bulk plasma. The ion density begins to decrease around $r/r_\mathrm{p} \sim 1.5$, because the expansion overcomes the ionization.The

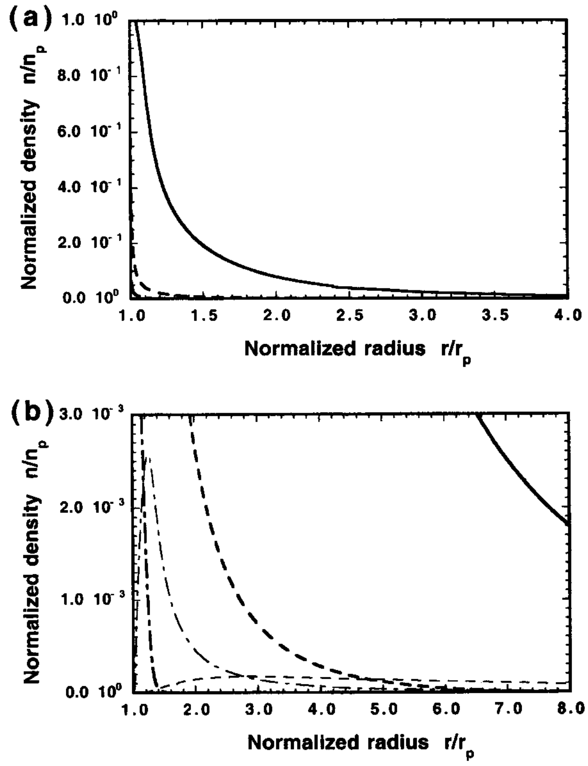

Fig. 1 Normalized density, n/n_p, as a function of normalized radius, r/r_p. Solid, dashed and dot-dashed lines show atom densities for the cases 1, 2 and 3, respectively. Thin lines show ion densities. Difference between (a) and (b) is scales of x- and y-axes.

same feature is found also in the case 2. A peak value of the ion density for the case 3 is greater and a peak position of it is nearer than ones for the case 2. In the case 1, the ion density is so small that the feature can not be observed. In order to estimate the ionization rate, we use the following equation:

$$R_{\mathrm{ion}} = \frac{\int_{r_p}^{\infty} 4\pi r^2 \, n_i \, dr}{\int_{r_p}^{\infty} 4\pi r^2 \, n_h \, dr} \qquad (15)$$

The resultant ionization rates, R_{ion}, are 0.0015, 0.30 and 0.75 for the cases 1, 2 and 3, respectively. Then, the ionization rate for the case 3 is clearly larger than the others.

Next, we consider the reason why the ionization rate is largest in the case 3, though the temperature of the electron in the bulk plasma is lowest. The energy source, H, provided by the electron depends on the heat flux, q, as shown by Eq. (13). q is expressed as q_∞ by Eq. (1) in the bulk plasma far away from the pellet. Since q_∞ is proportional to $n_\infty T_\infty^{3/2}$, it is clear that the q_∞ is smallest in the case 1 and q_∞ is largest in the case 3. Then, the ionization rate is smallest in the case 1, and one is largest in the case 3. In Fig. 2, circles show the conditions of the bulk plasmas in the cases 1, 2 and 3, where the horizontal and vertical lines are the electron density and temperature in the bulk plasma, respectively. R_G is a ratio of the ablation rate, G:

$$R_G = G / G_{\mathrm{Parks}} \qquad (16)$$

where G corresponds to the present calculation and G_{Parks} does to Parks calculation [3]: $G_{\mathrm{Parks}} = 1.15 \times 10^{16}$ r_p [cm]$^{4/3}$ n_∞ [cm^{-3}]$^{1/3}$ T_∞ [eV]$^{1.64}$. In the case 1 with the

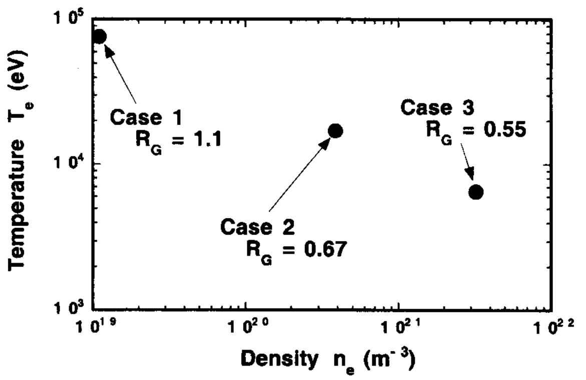

Fig. 2 Relation between the ablation rate and the bulk plasma. Horizontal and vertical lines are the electron density and temperature in the bulk plasma, respectively. Circles show the conditions of the bulk plasmas for the cases 1, 2 and 3.

quite small ionization rate, the ablation rate obtained in this paper is nearly equal to one of Parks model. It is about half value of one of Parks model, in the case 3 with the largest ionization rate. The energy of the heat flux is expended for the ionization, so that the ablation rate decreases. Therefore, we have found that the ablation rate is smaller than one of Parks model in the case 3, though the electron temperature in the bulk plasma is smaller than ones in the others.

The energy of the heat flux in any cases are large in comparison with ones in conventional experiments. In order to investigate the ablation rate in the experimental data, the thermal conduction should be added to Eq. (7) because a region dominated by the thermal conduction is created between the pellet surface and a position where the heat flux is reduced to zero. This region may be ignored in the case that the heat flux has high energy as used here because the flux can arrive around the pellet surface.

4. Conclusions

The fluid equations consisting of neutral atoms, ions and electrons are solved in an ablation cloud in order to construct a new ablation model including a realistic EOS of hydrogen and ionization and recombination. When the bulk plasma has a high temperature and a low density (case 1), the atoms evaporated from the pellet are hardly ionized around the pellet, so that the ablation rate is comparable with one of Parks model. In contrast with it, when the bulk plasma has a low temperature and a high density (case 3), the atoms evaporated are ionized so much around the pellet that the ablation rate becomes small compared with Parks model. In this case, the heat flux from the bulk plasma is expended for the ionization of the atoms. Investigations corresponding to present experimental data will be performed, including the thermal conduction, leading to a new scaling law of the ablation rate.

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