J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 353–356

Analysis of Pellet Ablation with Atomic Processes

ISHIZAKI Ryuichi, NAKAJIMA Noriyoshi and PARKS Paul B.[1]

National Institute for Fusion Science, Toki 509-5292, Japan

[1]General Atomics, San Diego, CA 92121, USA

(Received: 12 December 2003 / Accepted: 22 January 2004)

Abstract

A new type of a magnetohydrodynamics (MHD) code applicable to solid, liquid and gas states, "CAP" has been developed in order to investigate ablation process of a pellet with atomic processes in hot plasmas. One of the most important features of the code is to be able to treat recession of the pellet surface by ablation without any artificial boundary condition between the pellet and ablation cloud. A region excluding a magnetic field is induced because the magnetic pressure is overcome by the ablation pressure. It is found that a stationary shock wave is driven by ionization.

Keywords:

pellet, ablation, shock, MHD, perfect conductor

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 for building and sustaining a plasma density in an experimental system of past generation. However, in a large scale experimental system, *e.g.*, the Large Helical Device (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 (NGS) model set up by Parks and Turnbull [3]. The NGS model is derived by applying one dimensional, spherically symmetric and quasi-steady gas dynamics to the fluid ablating from a pellet in a thermonuclear plasma. And the model supposes the ablation cloud to consist of only one species, such as ground-state deuterium molecules. Though the model is very simplified, it has been providing many useful predictions and contributing to experiments of the pellet injection. However, more detailed analysis is required in these days when the pellet injection plays an important role in high-β plasmas in a large scale experimental system. Our final goal is to investigate the bulk plasma motion induced by the pellet injection including pellet dynamics itself, by developing a three dimensional fluid code dealing with both a neutral fluid and MHD plasma. As a first step, a new type of hydrodynamic code "CAP" has been developed where a various states of pellet are treated without assumptions.

The model of "CAP" is constructed as follows. When a pellet consisting of solid hydrogen is heated by an energy flux, it changes to liquid and gas during phase transition and subsequently to plasma during atomic process. In the present work, it is assumed that the ablation cloud consists of four species particles, namely, molecules, atoms, ions and electrons, and it behaves as one fluid due to charge neutrality and strong charge exchange except for incident plasma electrons encountering the cloud. The incident electron heat flux is considered by a kinetic treatment with a half-space Maxwellian distribution [4]. In addition, the equation of state (EOS) [5] is used to treat solid, liquid and gas. Dissociation and ionization are also included to cause deuterium to change to plasma. Since domain of the numerical simulation includes solid and gas regions, the Cubic-Interpolated Psudoparticle (CIP) method [6] is used in the code. The most essential point of the method is that it can calculate simultaneously incompressible and compressible regions without any artificial boundary conditions between them.

2. Basic equations

All species in the cloud 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 collisional 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 of the heat flux which drives the ablation. The ablation cloud consists of molecules, atoms, ions and electrons. Effects of atomic physics on the ablation

Corresponding author's e-mail: ishizaki@nifs.ac.jp

process, in particular dissociation and ionization in the ablation cloud, are considered. It is assumed that the species have same velocity (u) and temperature (T) due to high collision and charge exchange rate, so that they are regarded as one fluid with different densities. An electromagnetic force is ignored for simplicity. The dynamics in not only gas (ablation cloud) region but also solid (pellet) region are given by the following equations of mass, momentum and energy conservations:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho \nabla \cdot u, \tag{1}$$

$$\rho \frac{\mathrm{d}u}{\mathrm{d}t} = -\nabla p + \frac{1}{\mu_0}(\nabla \times B) \times B, \tag{2}$$

$$\rho \frac{\mathrm{d}e}{\mathrm{d}t} = -p\nabla \cdot u + H + \frac{\eta}{\mu_0^2}\left|\nabla \times B\right|^2 \tag{3}$$

$$\frac{\partial B}{\partial t} = \nabla \times \left(u \times B - \frac{\eta}{\mu_0} \nabla \times B \right) \tag{4}$$

where ρ is the total density, u the velocity, p the total pressure, e the total specific internal energy, H the heat source, B the magnetic field, μ_0 the permeability of free space and η the resistivity. When a solid is heated, it is transformed to gas (molecules) by absorbing the sublimation energy (ε_s = 0.01 eV). Subsequently, when the molecules are transformed to atoms by absorbing the dissociation energy (ε_d = 4.48 eV), the number density of the molecules decreases but one of the atoms increases. When the ablation cloud is more heated, the atoms are transformed to ions and electrons by absorbing the ionization energy (ε_i = 13.6 eV) and the number density of the atoms decreases but ones of the ions and electrons increase. Since the ablation cloud can be regarded as one fluid, p and e are respectively given by the following equations:

$$p = p_s + \left(\frac{1}{2} f_s + \frac{1}{2} f_d + f_i \right) \frac{\rho k T}{m}, \tag{5}$$

$$e = (1 - f_s) e_s + \left[\frac{f_s - f_d}{2(\gamma_m - 1)} + \frac{f_d + f_i}{\gamma - 1} \right] \frac{kT}{m} + \frac{1}{2} f_s \frac{k\varepsilon_s}{m} + \frac{1}{2} f_d \frac{k\varepsilon_d}{m} + f_i \frac{k\varepsilon_i}{m}, \tag{6}$$

where p_s and e_s is the pressure and specific internal energy in the solid, respectively, that should be determined by the EOS of the solid. γ_m and γ are ratios of the specific heats for molecules and atoms, respectively. k and m are the Boltzmann constant and nuclei mass, respectively. Fractions f_s, f_d and f_i are defined by $f_s = (2n_g + n_a + n_i)/n_t$, $f_d = (n_a + n_i)/n_t$ and $f_i = n_i/n_t$, respectively, where $n_t = 2n_s + 2n_g + n_a + n_i$. n_s, n_g, n_a and n_i are nuclei number densities of solid, gas, atoms and ions, respectively. These fractions are given by assuming the local thermodynamic equiriblium (LTE). The atomic process induced by the incident electrons encountering the cloud is not considered.

In the present model, only Ohmic (no runaway) discharges are considered so that the distribution of energies of electrons and ions of the bulk plasma may be taken as Maxwellian. Owing to the lower thermal velocity and shorter mean free path of ions, the thermal ion heat flux is too small to penetrate the ablation cloud and drive ablation. Since the electron gyroradius is much smaller than the size of the ablation cloud surrounding the pellet, orbits of the electrons are strongly tied to a single magnetic field line, when the electrons penetrate the ablation cloud. Then, the heating of the cloud can be calculated field line by field line. The heat flux, q, is solved by using a kinetic treatment for the deposition energy by plasma electrons incident to the cloud with a half-space Maxwellian distribution as shown in Ref. [4]. When z is supposed to be the spatial co-ordinate along the field line directed into the ablation cloud, the heat source H in Eq. (3) is given by $\partial q/\partial z$.

3. Ablation in 2D cylindrical axisymmetric system

Geometrical effects are investigated by multi-dimensional simulation where the cylindrical geometry (r, θ, z) is used as shown in Fig. 1. A spherical pellet is placed at the center of the geometry (r = 0, z = 0) and the heat flux encounters the pellet along the magnetic field (along z-direction), namely, it is anisotropic heating. Since physical quantities are assumed to be uniform in the θ-direction, this problem is reduced to two dimensional (2D) one. Boundary condition on the base of the cylinder is periodic one without flow that can go out. Boundary on the side of it is assumed to be a perfect conductor.

Figure 2 shows temporal evolution of the contour of magnetic pressure: $B^2/(2\mu_0)$. Initial conditions are the pellet radius r_p = 2 mm, electron temperature $T_{e\infty}$ = 2 keV and number density $n_{e\infty} = 10^{20}$ m^{-3} in the bulk plasma. Magnetic field is B_z = 1.12 T and B_r = 0 T. $T_{e\infty}$ and $n_{e\infty}$ are assumed to be constant through temporal evolution. When a pellet is heated, an ablation cloud with lower temperature and higher density than the bulk plasma is constructed surrounding the pellet. The magnetic pressure in the region around the pellet becomes very small because the magnetic pressure is overcome by ablation pressure. Lines of the magnetic force are bent by the ablation pressure as shown in Fig. 2. Figure 3 shows temporal evolution of the contour of pressure: p. It is found that expansion in r-direction is inhibited by the

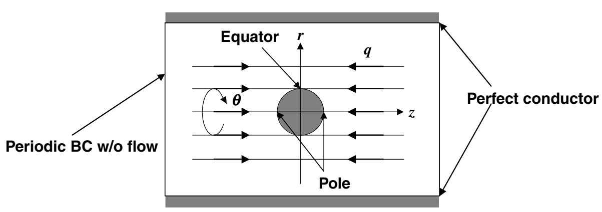

Fig. 1 2D axisymmetric cylindrical geometry. The bases of it are periodic boundary conditions without flow that can go out. The sides of it are perfect conductor.

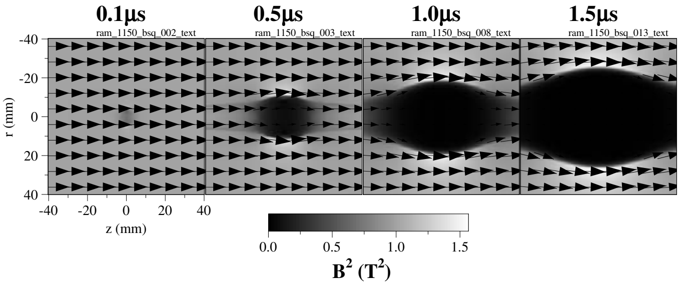

Fig. 2 Contour of $B^2/(2\mu_0)$ and vector of ***B***.

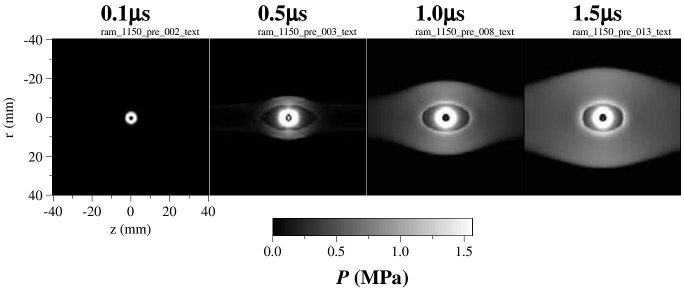

Fig. 3 Contour of *p*.

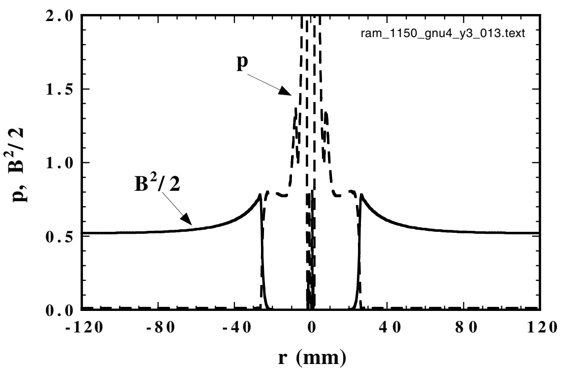

Fig. 4 Spatial profiles of *p* (dashed line) and $B^2/(2\mu_0)$ (solid line) in *r*-direction.

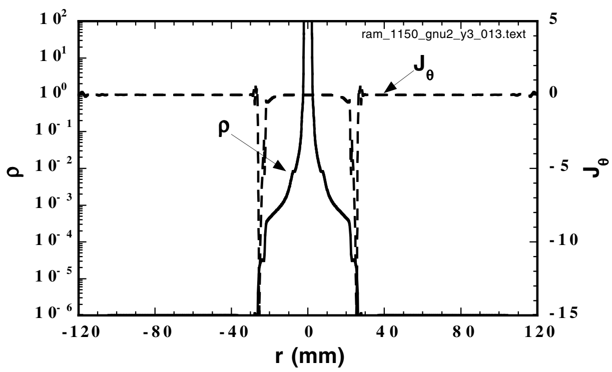

Fig. 5 Spatial profiles of ρ (solid line) and J_θ (dashed line) in *r*-direction. respectively.

magnetic pressure in comparison with one in *z*-direction. Figure 4 shows *p* and $B^2/(2\mu_0)$ in *r*-direction at 1.5 μs. The magnetic pressure is comparable to the ablation pressure at r ~ 30 mm where force balance is satisfied. The ablation cloud expands slowly as keeping the force balance between the magnetic pressure and ablation pressure. Figure 5 shows density ρ and current J_θ. It is found that there is a surface current at r ~ 30 mm and no current in the region. In other words, surface of the ablation cloud becomes perfect conductor, so that there is neither magnetic field nor current.

Figure 6 shows Mach number and fractional ionization by dashed and solid lines, respectively. Ablated particles around the pellet is accelerated by the ablation pressure

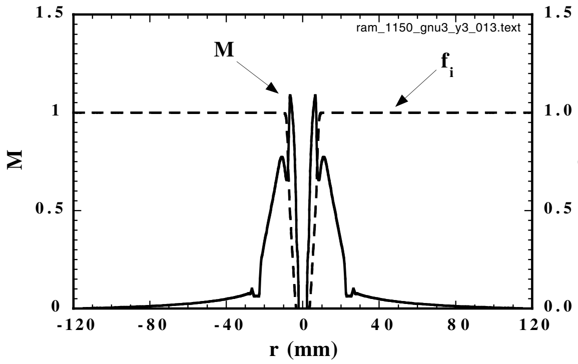

Fig. 6 Spatial profiles of *M* (solid line) and f_i (dashed line) in *r*-direction. respectively.

without the effect of the magnetic field. On the other hand, the flow is disturbed by the magnetic field out of the ablation cloud. Then, there are acceleration and deceleration phases in the ablation cloud as shown in Fig. 6. A jump structure is found to be driven in the acceleration phase. That is a shock wave because the flow is supersonic ahead of that structure and subsonic behind it. The shock is found to be driven in the region where the ablation particles ionize ($0 < f_i < 1$). Since the neutral particles loose their energy by ionization in that region, their kinetic and internal energies are hard to the ablation cloud and drives a shock.

4. Conclusions

Two dimensional MHD code "CAP", treating with a neutral in various states of matter and plasma simultaneously, has been developed to investigate the pellet ablation with atomic processes and anisotropic heating from bulk plasmas. A region excluding a magnetic field is induced by ablation pressure because it overcomes the magnetic pressure. In other words, there is neither magnetic field nor current in the ablation cloud because surface of the ablation cloud behaves as a perfect conductor. It is shown that a stationary shock wave is induced by ionization.

References

[1] L.R. Baylor *et al.*, Nucl. Fusion **32**, 2177 (1992).
[2] D.J. Rose, Culham Laboratory Technology Division, Memorandum, No. 82 (1968).
[3] P.B. Parks and R.J. Turnbull, Phys. Fluids **21**, 1735 (1978).
[4] P.B. Parks *et al.*, Phys. Plasmas **7**, 1968 (2000).
[5] R.L. More, Phys. Fluids **31**, 3059 (1988).
[6] T. Yabe and P.Y. Wang, J. Phys. Soc. Jpn. **60**, 2105 (1991).