Pulse shape dependence of vapor shielding efficiency during transient loads

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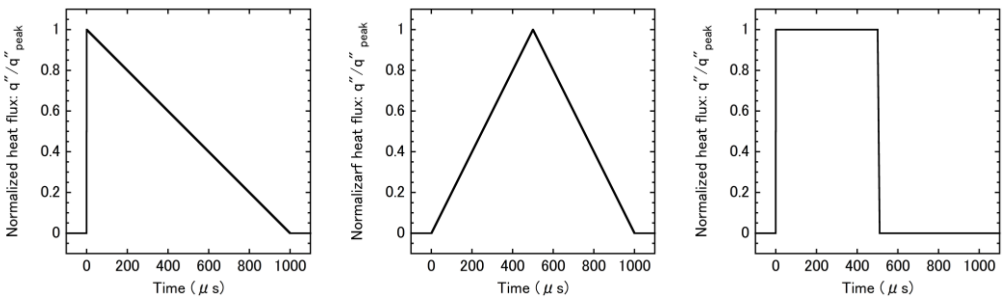
1. Introduction

Erosion of wall materials during transient events at ITER and future fusion devices is a large concern. Melting, vaporization, and ablation of wall materials will be caused by the extensive heat loads. The vapor shielding can be an inherent protection mechanism against the wall erosion. Interaction between the generated vapor from surface and the incoming plasma loads brings the dissipation of plasma energy. The authors are developing a particle-in-cell (PIC) based simulation code [1,2], called PIXY, for simulations of the vapor shielding in fusion devices. During the vapor shielding, the number of surface-ejected particles is varied over a very wide range according to the surface temperature. Thus, a weighted particle model is applied in order to treat the reasonable number of numerical super-particles.

Using the PIXY code, wall erosion under a rectangle pulse shape with a fixed time duration (0.2 ms) was investigated previously [2]. Meanwhile, in the transient heat loads, it is known that the erosion is strongly dependent on the pulse shape [3]. Thus in the present paper, pulse shape dependence of wall erosion is studied using the PIXY code. Two triangle pulse shapes, (a) negative ramp and (b) symmetric triangle, with a fixed time duration (1.0 ms) are examined by comparing to (c) rectangle pulse shape with a half duration (0.5 ms). Time evolution of heat flux (q") of these pulse shapes are illustrated in figure 1. These three pulses have the same total energy density and the same peak heat flux (q''_{peak}).



(a) (b) (c)

Figure 1 Pulse shapes of heat flux tested in this study: (a) Negative ramp, (b) Symmetric triangle, and (c) Rectangle.

2. Numerical Model

The PIXY code is a 1d3v (1 dimension in space and 3 dimensions in velocity) PIC code combined with a wall model. The heat flux to the wall is calculated by summing all super-particle energies reaching to the wall. Then the heat flux is used as a boundary condition for a heat transfer calculation in the first wall. From the heat transfer calculation, the temperature depth profile is determined. Based on the vapor pressure as a function of the surface temperature, a vapor emission rate is calculated. As well as this vaporization, ablation is considered. A wall layer exceeding a threshold temperature is counted as ablated. The threshold temperature is assumed as the boiling point at the atmospheric pressure. The vapor and ablated wall particles are then ejected as super-particles in the PIC calculation. In the PIC calculation, vapor-plasma interactions are solved using the OPEN-ADAS[4] library data. Further calculation details are found in ref [2]. In this study, a fixed temperature (1 keV) plasma to a divertor wall under 2T magnetic field with a 6° incident angle is simulated. By changing the incoming plasma density, transient loads with the energy density up to 8 MJ/m^2 are studied.

3. Numerical Result

Figure 2 shows the time evolution of heat flux reaching to the wall in cases of the negative ramp and symmetric triangle with the total energy density of 4 MJ/m^2. In both cases, the vapor shield case shows a smaller heat flux compared with the no vapor shield case. Ion and electron components of the heat flux in the vapor shield cases are also plotted. The decrease of ion heat flux is observed in the vapor shield case, while the dissipation of the electron energy is not clearly found. It can be considered that the present simple models for atomic-molecular reactions [2] are still incomplete. First, the radiation cooling power is underestimated by a single-Maxwellian estimation. Second, the ionization-state probability is not well followed for a large weight tungsten particle. Both can cause the small dissipation of the electron energy in the present simulation. Further investigations are necessary for the atomic-molecular reaction models.

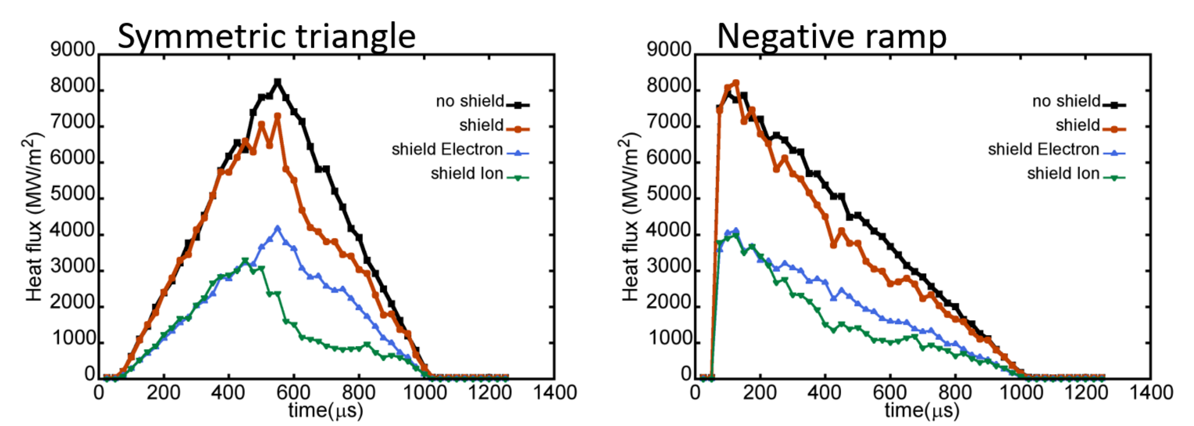


Figure 2 Time evolution of heat flux of symmetric triangle and negative ramp pulse. No vapor shield case and vapor shield case are compared. Breakdowns of the vapor shielding case (heat flux of ion and electron) are also shown.

By changing the plasma density, the energy density of a pulse is scanned while the pulse duration and the plasma temperature are fixed. The erosion thickness as a function of the energy density is summarized in figure 3. As well as the three pulses obtained in this study, result of 0.2 ms rectangle pulse shots from ref [2] are shown. For all pulse shapes, the vapor shield (VS) case show smaller erosion than the non vapor shield (no VS) case. Comparing the 0.5ms and the 0.2 ms rectangle pulses, the erosion thickness is smaller in case of the 0.5 ms cases at the same energy density. In the longer pulse time, the peak heat flux becomes smaller, thus the maximum surface temperature and the erosion become smaller.

Comparing the symmetric triangle and the negative ramp pulses, the erosion thickness is smaller in case of the negative ramp cases. This is explained as follows. In triangle pulse shapes, the maximum surface temperature becomes higher when the peak heat flux comes later. This is caused by a slow thermal diffusion within a pulse time. Plus, the thermal conductivity becomes smaller as temperature increases. Then the peak heat flux comes later, the remained heat and the smaller thermal conductivity cause higher surface temperature and higher erosion. Thus, comparing the

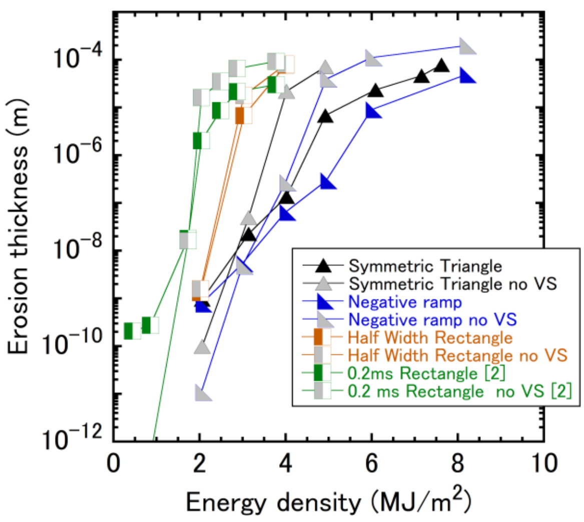


Figure 3 Erosion thickness as a function of energy density for different pulse shapes.

symmetric triangle and the negative ramp, the peak comes later in the symmetric triangle case which shows the larger erosions.

Comparing between the triangle and the rectangle pulse shapes, the triangle cases shows better vapor shielding efficiency. Vapor ejected at the peak heat flux effectively dissipates the incoming plasma energy after the peak. Thus, it is predicted that a longer pulse time and a negative ramp type pulse shape are favorable to reduce the wall erosions.

4. Summary and Discussion

The PIXY code (weighted PIC with a wall model) was used for the vapor shielding simulation with different pulse shapes. Erosion caused by two triangle pulse shapes and a rectangle pulse shape were studied and summarized as a function of energy density. In all cases, the erosion thickness is reduced by the vapor shielding while the shielding rate can be underestimated due to the smaller radiation power and smaller ionization rate. The erosion becomes smaller as pulse length becomes longer. Plus, in case of triangle pulse shapes, the erosion thickness is reduced when the peak flux comes earlier.

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