Self-consistent 3D calculation of the ablation rate of pellets with high injection velocities

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Introduction

Pellets of frozen hydrogen isotopes are injected into thermonuclear devices for refueling, for diagnostic use, or for quenching the plasma prior to a hard disruption. A pellet injected into hot plasma ablates at a rate defined by the balance of the energy fluxes reaching the pellet surface. The relatively cold and high-density cloud evolving around the ablating pellet represents a massive disturbance for the recipient plasma. The ablated substance is heated by the energy fluxes carried by the background plasma particles along the magnetic field lines and by thermal diffusion in the three directions. The partially or fully ionized pellet material becomes magnetically confined in the poloidal planes but expands unimpeded along the magnetic field lines. The cloud evolving around the ablating pellet modifies the energy fluxes affecting the surface of the pellet.

A time-dependent 3D computational model is being developed in a Cartesian coordinate system in which the complete set of resistive MHD conservation equations, supplemented by Maxwell's equations, Ohm's generalized law, and a number of finite rate equations, is being solved, see [1]. Finite volume methods are applied to compute the above system of equations. The x-y planes represent poloidal planes, the z=0 is considered to be a plane of symmetry. The z-direction is discretized by a sequence of poloidal planes, the x-y discretization is identical for all the poloidal planes. In this discretization of the three dimensional space, structured numerical hexahedral cells are formed whose two opposite sides (in the z-direction) reside on two consecutive poloidal planes . The discretization in the three directions can be uniform, non-uniform. or a combination of both.

The ablation rates of moving or stationary pellets are computed self-consistently by calculating the energy flux balance at the pellet surface. In this report, the ablation rate, of stationary and moving pellets, is considered. Numerical problems caused by coarse grids, such as numerical oscillations of the computed ablation rates at high pellet injection velocities, are discussed.

Ablation rate and deposition of ablated particles

In this system, a spherical pellet of given radius r_p maybe stationery or moving in the z=0 plane. Moving pellets have only x and/or y velocity components. In the results presented here the velocity has only a x component and the pellet is moving from left to right. The circle of radius r_p is mapped on the discretized x-y plane and the energy fluxes are summed over the area of the circle. By obtaining the power irradiating the pellet surface; and by dividing with the ablation energy per particle we obtain the ablation rate, in particles per second.

Here we consider the deposition of the ablated particles onto the numerical grid by three different methods. In the first method the ablated particles are distributed uniformly over a circle of r_p, second method ablated particles are distributed uniformly over a circle of radius $2r_p$, and thirdly uniform distribution of the ablated particles over a circle of radius $3r_p$.

Results and comments

Here we present numerical results pertaining to the ablation rate for stationery and moving pellets. Initially the 3-D computational space is filled uniformly with deuterium plasma of temperature T_e and particle density n_e, the magnetic field has only one component B_z (which is parallel to the z-axis). At time=0 the pellet is placed in the center of the x-y plane. The region over the center of the x-y plane has been discretized uniformly with $\Delta x = \Delta y = 0.002m$, also Δz=0.002m. Figure 1 shows the ablation rate and the pellet radius as functions of time for a stationery pellet of initial r_p=1mm immersed in a recipient plasma: of $n_e=10^{20}$ m^{-3}, B_z=1T, (1) T_e=1keV, and (2) T_e=2keV. It is clearly shown for the case (1) T_e=1keV the pellet has been completely ablated in 62μs, and for T_e=2keV the pellet has been completely ablated in 46μs. Figure 2 shows the contours of (a) temperature in a slice(x-y plane) at z=0, and (b) the contours of particle density in a slice parallel to the x-z plane and normal to the y-axis, at the time instant t=10μs for the case (2) T_e =2keV. In these two stationery pellet scenarios the ablated particles are deposited uniformly within one r_p.

Results pertaining to the moving pellets are shown in Fig.3. Here we consider two scenarios (a) pellet injection velocity v_p=1000 m/s, and (b) v_p =2000 m/s, the initial recipient plasma has T_e=2keV, n_e=10^{20} m^{-3}, B_z =1T, and initial r_p = 1mm. We consider three deposition methods. In Fig.3 (a) it is clearly shown that the periodicity of the small oscillations in the ablation rate is 2μs, this is related to the $\Delta x/v_p$ which is 2μs, similarly for case (b) with injection velocity of 2000 m/s the periodicity is 1μs. It is clearly shown that the deposition methods with $2r_p$ and $3r_p$ do reduce the amplitudes of the oscillation in the ablation rate. Refining the numerical grid, e.g. taking Δx=1mm, does reduces the amplitudes of these oscillations, but the cpu time increases dramatically. In a typical scenario which takes 50μs the cpu time for a single processor is over 250 hours.

A more refined deposition method, by depositing ablated particles on a circular ring around the solid pellet and in a Maxwelian distribution is currently being investigated.

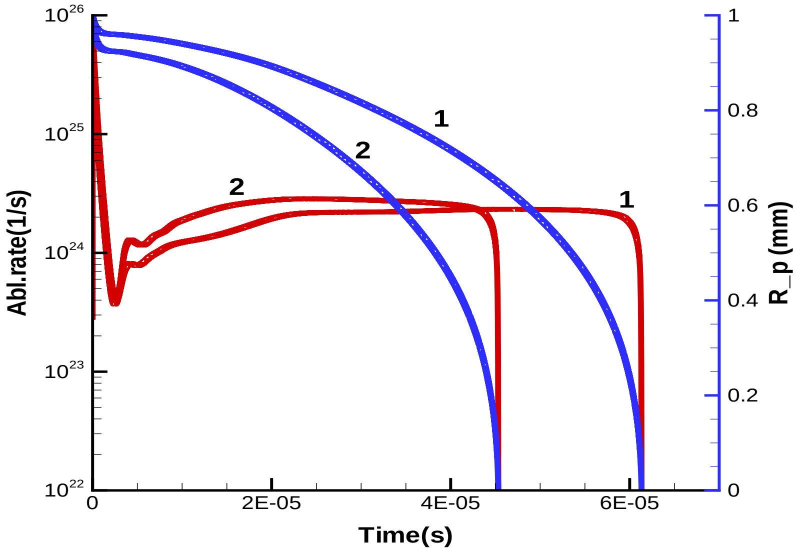

Fig.1. Plots of ablation rate (red) and pellet radius (blue) as function of time for recipient plasma temperature of 1 keV(1) and 2 keV(2), for stationery pellet of initial pellet radius 1 mm.

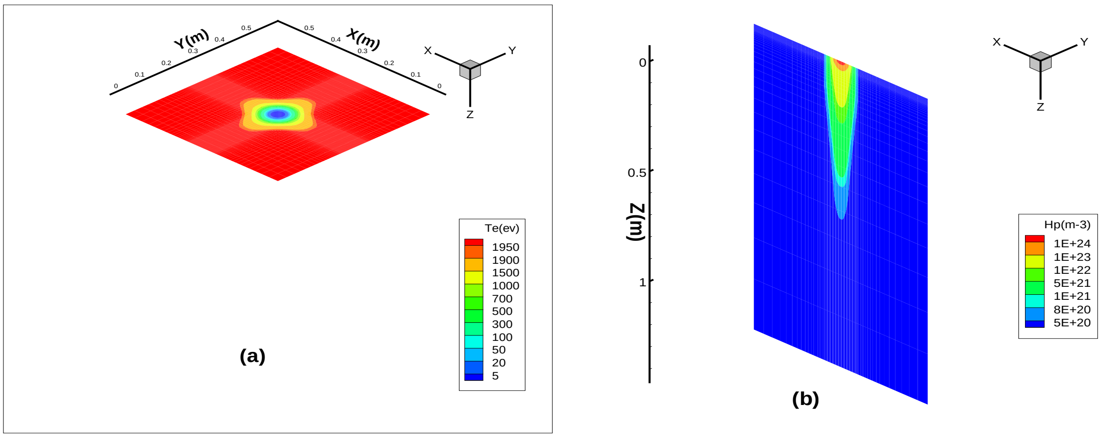

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*Fig.2, Plot of contours for (**a**) the temperature T_e in a slice (x-y plane) at z=0, and (**b**) the particles density contours in a slice parallel to the x-z plane and at the middle of the y-axis, at the time instant t=10μs, for the stationery pellet will initial temperature of recipient plasma T_e=2keV..*

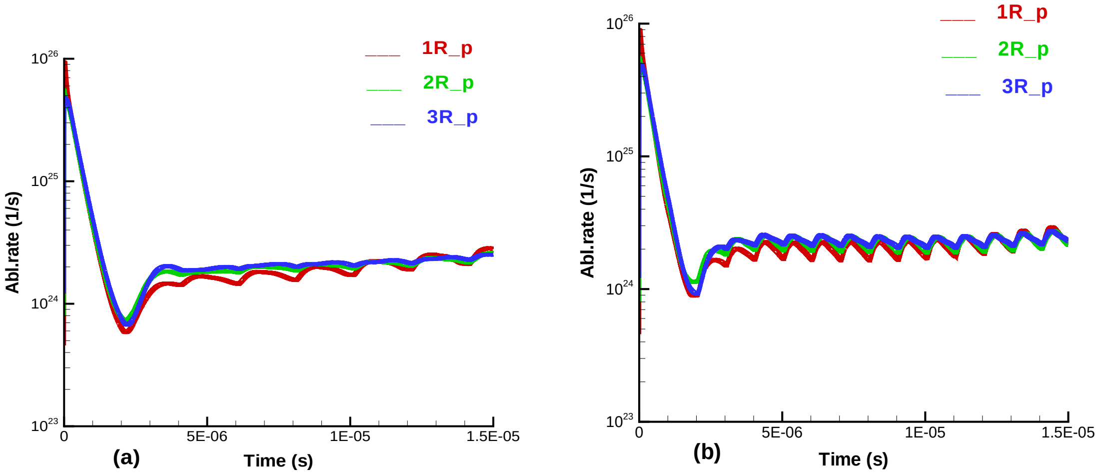

*Fig.3, Plots of ablation rate for pellet injection velocities (**a**) 1000 m/s and (**b**) 2000 m/s. The ablated particles are deposited within one (red) or two (green) or three (blue) pellet radii, uniformly distributed.*

References

[1] P. J. Lalousis, L. L. Lengyel et. al., Two (‘plus one ‘) dimensional simulations of pellet cloud evolution in the poloidal plane with a prescribed neutral particle source strength, Plasma Phys. Control Fusion 50(2008) 085001