Simulation of pellet ablation for tokamak fueling with ITAPS front tracking

Roman Samulyak[1,2], Tianshi Lu[2], Paul Parks[3], James Glimm[1,2] and Xiaolin Li[1]

[1] Department of Applied Mathematics and Statistics, Stony Brook University, Stony Brook, NY 11794, USA
[2] Computational Science Center, Brookhaven National Laboratory, Upton, NY 11973, USA
[3] General Atomics, P.O. Box 85608, San Diego, CA 92186-5608

E-mail: rosamu@ams.sunysb.edu

Abstract. A magnetohydrodynamic numerical model and parallel software for the ablation of cryogenic deuterium pellets in the process of tokamak fueling has been developed based on the method of front tracking of ITAPS Center. The main features of the model are the explicit tracking of material interfaces, a surface ablation model, a kinetic model for the electron heat flux, a cloud charging and rotation model, and an equation of state accounting for atomic processes in the ablation cloud. The software was used for the first systematic studies of the pellet ablation rate and properties of the ablation channel in magnetic fields. Simulations revealed new features of the pellet ablation such as strong dependence of the radius of the ablation channel and ablation rate on the "warm-up" time and supersonic spinning of the ablation channel.

1. Introduction

The injection of small frozen deuterium-tritium pellets is an experimentally proven method of tokamak refueling [1]. Pellet injection is currently seen as the most likely refueling technique for the International Thermonuclear Experimental Reactor (ITER). In order to evaluate the efficiency of this fueling method, it is necessary to determine the pellet ablation rate.

The ablation of tokamak pellets and its influence on the tokamak plasma have been studied by using several analytical and numerical approaches (see [2] and references therein). The inherent limitation of the previous ablation models has been the the absence of a rigorous inclusion of important details of physics processes in the vicinity of the pellet and in the ablation channel and insufficient accuracy of numerical models due to extreme change of thermodynamics states on short length scales. The motivation of the present work is to improve both the accuracy of computational models by using the front tracking technology of the Interoperable Technologies for Advanced Petascale Simulations (ITAPS) Center [3] and physics modeling of the interaction of the pellet ablation channel with the tokamak magnetic field. The present work is a continuation of [4], which introduced sharp interface numerical MHD model for the pellet ablation but omitted effects of charging and rotation of the pellet ablation channel. Both sharp interface numerical techniques and the resolution of complex physics processes in the pellet ablation channel are important, not only for calculating pellet ablation rates and the fueling efficiency, but also for understanding striation instabilities in tokamaks [5].

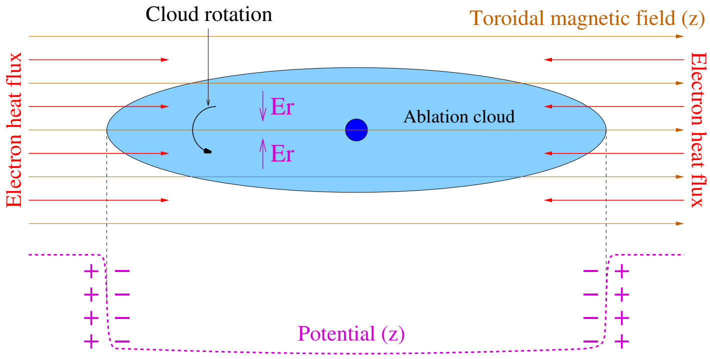


Figure 1. Schematic of physics processes associated with the ablation of deuterium pellet in a tokamak.

2. Main physics processes

In this section, we briefly summarize the main physics processes associated with the ablation of a cryogenic deuterium pellet in a tokamak magnetic field (see Fig. 1). Hot electrons traveling along the magnetic field lines hit the pellet surface causing a rapid ablation. A cold, dense, neutral gas cloud forms around the pellet and shields it from the incoming hot electrons. After the initial stage of ablation, the most important processes determining the ablation rate occur in the cloud. The cloud away from the pellet heats up above the dissociation and then the ionization levels and partially ionized plasma channels along the magnetic field lines. As shown in [4], this process can be described by the system of magnetohydrodynamics (MHD) equations in the low magnetic Reynolds number approximation. The plasma cloud stops the incident plasma ions at the cloud / plasma interface, while the faster incident electrons penetrate the cloud where their flux is partially attenuated depending on the cloud opacity. We employ the kinetic model for the hot electron-plasma interaction proposed in [6]. The tendency of the background plasma to remain neutral confines the main potential drop to a thin sheath adjacent to both end-faces of the cloud. Inside the cloud, the potential slowly changes along each field line. Since the cloud density and opacity vary radially, the potential inside the cloud varies from field line to field line, causing $E \times B$ cloud rotation about the symmetry axis. The potential can be explicitly found by using kinetic models for hot currents inside the cloud [5]. The fast cloud rotation widens the ablation channel, redistributes the ablated gas, and changes the ablation rate. We believe that it also causes striation instabilities observed in pellet injection experiments [5].

3. Numerical method

In this section, we describe numerical ideas implemented in the FronTier-MHD code. The system of MHD equations in the low magnetic Reynolds number approximation is a coupled hyperbolic-elliptic system in a geometrically complex moving domain. We have developed numerical algorithms and parallel software for 2D and 3D simulations of such a system [7] based on the ITAPS front-tracking technology [8].

The numerical method uses the operator splitting. We decouple the hyperbolic and elliptic parts of the MHD system for every time step. The mass, momentum, and energy conservation equations are solved first without the electromagnetic terms (Lorentz force). We use the front tracking hydro code FronTier with free interface support for solving the hyperbolic subsystem. In general case, the electromagnetic terms are found from the solution of the Poisson equation for the electric potential in the conducting medium using the embedded boundary method, as described in [7]. In the 2.5D axisymmetric model for the pellet ablation, the elliptic step is eliminated as the current density in each point of the ablation cloud is a function of the hydrodynamic state and some integrated quantities along the corresponding magnetic field line. Solving of a modified 3D Poisson problem is required in our current work on 3D pellet ablation. At the end of the time step, the fluid states are integrated along every grid line in the longitudinal direction in order to obtain the electron heat deposition and internal hot currents. The heat deposition changes the internal energy and temperature of fluid states and therefore the electrical conductivity. The Lorentz force and the centrifugal force are then added to the momentum equation.

FronTier represents interfaces as lower-dimensional meshes moving through a volume-filling grid (Fig. 2). The traditional volume-filling finite-difference grid supports smooth solutions located in the region between interfaces. The location of the discontinuity and the jump in the solution variables are defined on the interface. A computational stencil is constructed at every interface point in the normal and tangential direction, and stencil states are obtained through interpolation. Then Euler equations, projected on the normal and tangential directions, are solved. The normal propagation of an interface point employs a predictor-corrector technique. We solve the Riemann problem for left and right interface states to predict the location and states of the interface at the next time step. Then a corrector technique is employed that accounts for fluid gradients on both sides of the interface. Specifically, we trace back characteristics from the predicted new interface location and solve Euler equations along characteristics. After the propagation of the interface points, the new interface is checked for consistency of intersections. The untangling of the interface at this stage consists in removing unphysical intersections and rebuilding a topologically correct interface. The update of interior states using a second-order conservative scheme is performed in the next step. The tracked interface allows us to avoid the integration across large discontinuities of fluid states and thus eliminate the numerical diffusion. The FronTier code has been used for large-scale simulations on various platforms including the IBM BlueGene supercomputer New York Blue at Brookhaven National Laboratory.

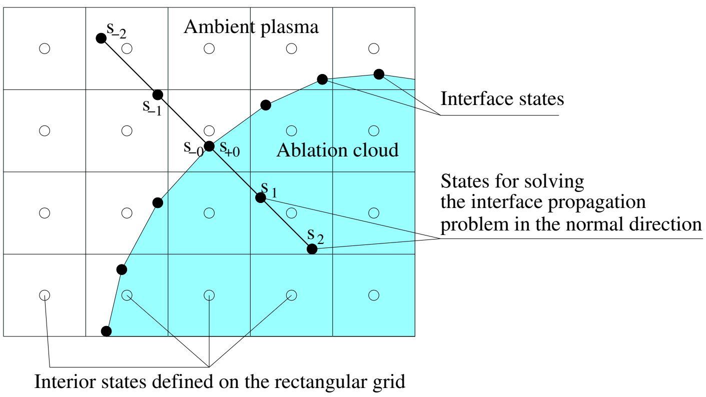
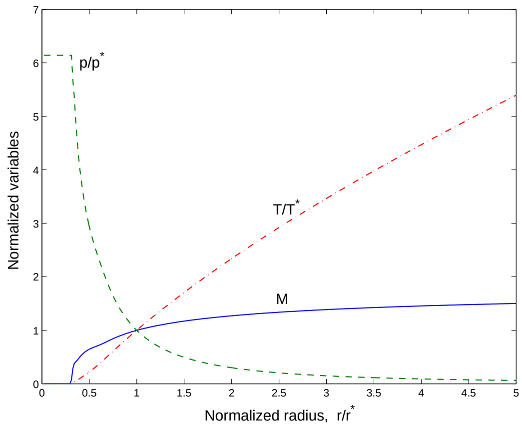


Figure 2. Rectangular grid, interface, and states for the method of front tracking. States contain density, momentum, and energy density of the fluid (plasma) and references to the EOS model and other parameters.

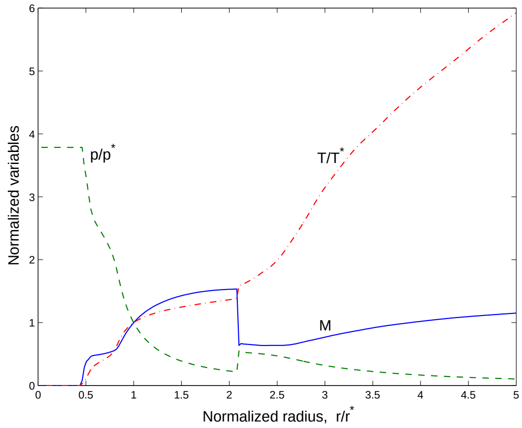
4. Simulation results

The numerical pellet ablation model was benchmarked in [4] with the theoretical Neutral Gas Shielding model [9] and previous pure-hydrodynamic numerical simulations [6]. We reproduced the double transonic layer in the ablation cloud induced by atomic processes of dissociation and ionization (Fig. 3) and obtained an excellent agreement of cloud properties and ablation rates. Performing 2D pure hydrodynamic simulations, we explained the factor of 2.2 reduction of the pellet ablation rate of the axially symmetric model compared to the spherically symmetric one. In the literature, it was attributed to the directional heating [6]. We showed that the directional heating is responsible for only 18% of the ablation rate reduction, and the effect is caused mainly by the difference of ablation rates induced by the Maxwellian and monoenergetic electron heat fluxes [4].

Then we performed the first systematic studies of pellet ablation rates and channel properties in magnetic fields. The ionization of the pellet ablation cloud by the electron heat flux leads



(a) Polytropic EOS



(b) Plasma EOS

Figure 3. Normalized ablated gas profiles at $10\,\mu s$ in 1D spherically symmetric model of (a) ablation without atomic processes (polytropic EOS), and (b) with atomic processes (plasma EOS). The solid, dashed, and dash-dotted lines are M, p/p^*, and T/T^* as functions of r/r^*, respectively.

to the channeling of the ablation flow along magnetic field lines. We found that this effect is sensitive to the parameter "warm-up time" and the cloud rotation. Longer warm-up time leads to a slower increase of temperature and wider ablation flow channels. The rotation of the cloud also widens the ablation channel. The channel radius increased from 2.3 cm without cloud rotation to 2.8 cm with rotation. The cloud pressure was lowered by 7% and the pressure peak in the cloud was shifted to $r = 1.5$ cm. Along the z-axis, the density was lower with cloud rotation due to the centrifugal force, which corresponded to less shielding. Fig. 4 shows isosurfaces of pressure in the steady-state ablation cloud.

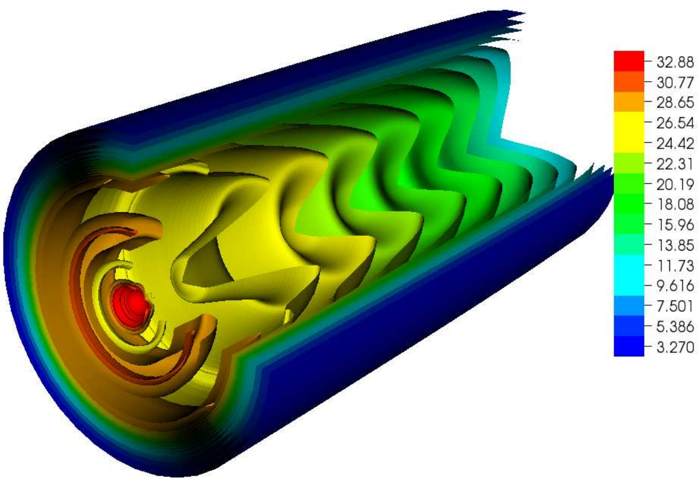


Figure 4. Isosurfaces of pressure in the steady-state ablation cloud.

Figure 5 plots the Mach number of the rotational velocity, $M_\theta = u_\theta/c$, for the steady-state flow with cloud rotation. It has transonic distribution, and the sonic points are located in the ablation channel close to the channel boundary. With cloud rotation, the steady-state ablation rate increased from 195 g/s to 260 g/s. We conclude that the cloud rotation increases the ablation rate because of to the widening of the ablation channel.

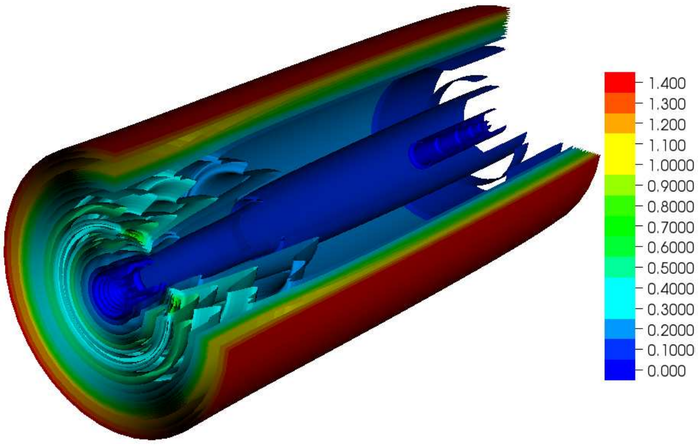


Figure 5. Isosurfaces of rotational Mach number in the steady-state ablation cloud.

5. Conclusions and future plans

Using the front tracking technology of the ITAPS Center, we have developed novel mathematical models, numerical algorithms, and computational software for the numerical simulation of free surface magnetohydrodynamic (MHD) flows of conducting liquids and flows of partially ionized plasmas in the presence of phase transitions and high power particle beams. The software was applied to the numerical simulation of the pellet ablation for tokamak fueling. In our recent work, the pellet ablation rate and lifetime in magnetic fields were systematically studied for the first time and compared with theory and experimental databases. Simulations revealed several new features of the pellet ablation. In the MHD simulations, the Lorentz force funnels the ablation flow into an extended plasma shield, which intercepts the incident plasma heat flux and reduces the ablation rate, depending on the rise time of the heat flux seen by the pellet. Shorter warm-up times lead to narrower ablation channels and reduced ablation rate. This new feature implied that pellets transversing strong plasma gradients, as in the edge pedestal region of the ITER plasma, could have significantly lower ablation rates (higher fueling efficiency) if injected at higher velocity. Using a new model for the potential distribution in the ablation channel, we also demonstrated the supersonic rotation of the channel, a phenomenon most likely causing the striation instabilities. The study of striation instabilities will be the focus of our future research.

Acknowledgments

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