Quasi two-dimensional hydrodynamic simulation of pellet ablation and plasmoid expansion

D. Wágner[1], S. Kálvin[2]

[1] *Budapest University of Technology and Economcs, Budapest, Hungary*

[2] *MTA KFKI–Research Institute for Particle and Nuclear Physics, EURATOM Association,Budapest, Hungary*

Introduction

Pellet injection is being considered as a prospective method of refuelling future tokamaks. In order to estimate the efficency of this fuelling method it is necessary to determine the pellet ablation rate in plasma.

The ablation of pellets has been studied using several semi-analytical and numerical approches. The existing simple hydrodynamic models take the cloud expansion either spherically symmetric or field aligned. A recent 2D magnetohydrodynamic simulation [1] includes both, but the model is computationally expensive thus its use for a fast, predictive ablation code is problematical. The main motivation for the present study is to develop a simple, hydrodynamic model of pellet ablation which includes *both* the spherical symmetric and channel flow phase of the cloud expansion at the same time it calculates the ablation rate fast.

The model

As the pellet is injected into the plasma, the incoming hot particles are heating its surface and the pellet starts to ablate neutral atoms and molecules. These particles form a dense cloud around the pellet. It is shown that the dynamics of this pellet cloud is the most important aspect of this phenomenon. Close to the pellet, as long as the cloud gets ionized its expansion is spherical. Far from the pellet surface the ablatant gas is almost fully ionized and it moves along the magnetic field lines of the plasma. Concerning the transition from one extreme to the other we can assume that the early spherical streamlines smoothly turn in the direction of the magnetic field lines (see Fig. 1.).

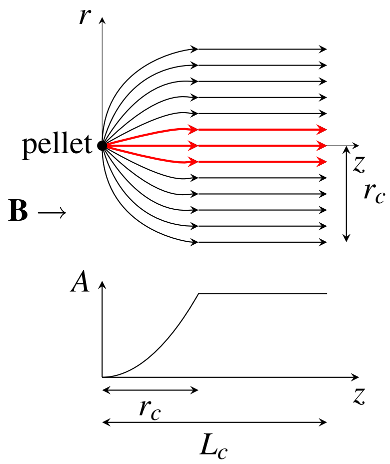

Figure 1: The initial spherical, then field aligned expansion of the pellet cloud, and the quasi 2D geometry.

Following this idea we have given forth the well-known

	Q2D	FronTier code [1]
spherical, without ionization (NGS)	$132\,\mathrm{g/s}$	$112\,\mathrm{g/s}$
spherical, with ionization	$130\,\mathrm{g/s}$	$106\,\mathrm{g/s}$
finite r_c	$29\,\mathrm{g/s}$	$28\,\mathrm{g/s}$
parameters	$r_c = 8\,\mathrm{mm}$	$n_e = 4\,\mathrm{T}$
	$r_p = 2\,\mathrm{mm}$ $n_e = 10^{20}\,\mathrm{m}^{-3}$, $T_e = 2\,\mathrm{keV}, L_c = 150\,\mathrm{mm}$	

and widely used transonic flow ablation model (TF [2]) by solving the same hydrodynamics (HD) equations but in a different geometry. In the light of the presence of the magnetic field we realized the ablatant flow in a nozzle with a varying cross section. First, the nozzle's cross section is proportional to the second power of the distance from the pellet (spherical expansion), then after an r_c channel radius it remains constant. Between the two extrema we assumed a smooth transition from one to another. It is clear that in our model the capability of the magnetic field of keeping together the ionized gas is analogous with forcing the ablatant flow into a tube with a constant crosssectional area (channel flow).

Electrons originated from the background plasma heat the cloud. In the quasi two-dimensional model the used heat flux model is identical to the one described in [3]. We omitted the detailed modeling of the solid-gas transition on the pellet surface. The boundary condition of the pellet's side is a simple rigid wall. In front of this the pellet is represented by a mass and energy source. At the end of the cloud we model a free expansion, where the $Ma = 1$ condition is used [1].

Validation

Before we used the quasi two-dimensional model for ablation rate calculations, the given profiles have been compared to the well-known spherical symmetric and MHD profiles. The same validation process was followed as that in [1]. At $r_c \to \infty$ both the spherical symmetric flow pattern and the ablation rate values agree well (see Tab. .).

If one compares the given profiles at finite r_c by the quasi 2D model, and the longitudinal (z) distribution of the flow properties from a 2D fully MHD calculation [1], it can be seen that they are almost identical. Moreover the calculated ablation rates are practically the same (Tab.). This shows us that the *quasi two-dimensioal* label is appropriate.

Estimating the channel radius

The quasi two-dimensional model contains two external parameters: the r_c channel radius and the L_c channel length. Here a simple estimate is presented for the former one.

	n_e	T_e	r_p	B_t
"ASDEX"	$5 \cdot 10^{19}\mathrm{m}^{-3}$	1 keV	0.7 mm	1 T
"ITER"	$10^{20}\mathrm{m}^{-3}$	2 keV	2 mm	4 T

Table 1: Typical model parameters for the calculations.

Firstly, we assume an s trajectory for a small piece of ablatant. Simply, we consider s as the trajectory of the case of spherical expansion. Then let us define r_c as the point where the accumulated momentum originated from the $\mathbf{J} \times \mathbf{B}$ force equals to the gathered inertial momentum.

$$\int_0^{t_0} JB \,\mathrm{d}\tau = \rho v\left(s(t_0)\right)$$

gives t_0, where the J current density is caused by the motional electric field and it is responsible for stopping the radial expansion of the cloud. Then we calculate

$$r_c = \int_0^{t_0} v(s(\tau))\,\mathrm{d}\tau,$$

along the s trajectory. This gives a rough estimate for the channel radius. Note that above the ρ density and the v velocity are taken from the spherical symmetric profile, though a finite r_c calculation can be made with the given value and one can recalculate the channel radius with these new profiles. This way r_c can be determined such a self consistent manner.

L_c was arbitrary set to 150 mm as it was in [1].

Calculations

For the sake of simplicity let us introduce two model scenarios „ASDEX" would represent the current days experiments , while "ITER" would corresponds to future larger pellets shot into a hotter plasma with a larger toroidal magnetic field. Tab. 1. shows the typical model parameters.

Here the dependence of the ablation rate on the pellet radius is presented. Fig. 2. shows ablation rates (G) and ablation rates over the corresponding ablation rate obtained from a spherical symmetric calculation (G_s). It can be seen, that at smaller pellets the spherical symmetric model, and therfore the NGS scaling works well, but for larger pellets a significant deviation is expected from that.

Conclusions

A quasi two-dimensional ablation model is presented. It takes into account the atomic processes and calculates the ablation rate. It has been proven that the developed model is consistent with the existing hydrodynamic simulations. The calculated profiles and ablation rate values are also in good agreement with those provided by a more sophisticated magnetohydrodynamic

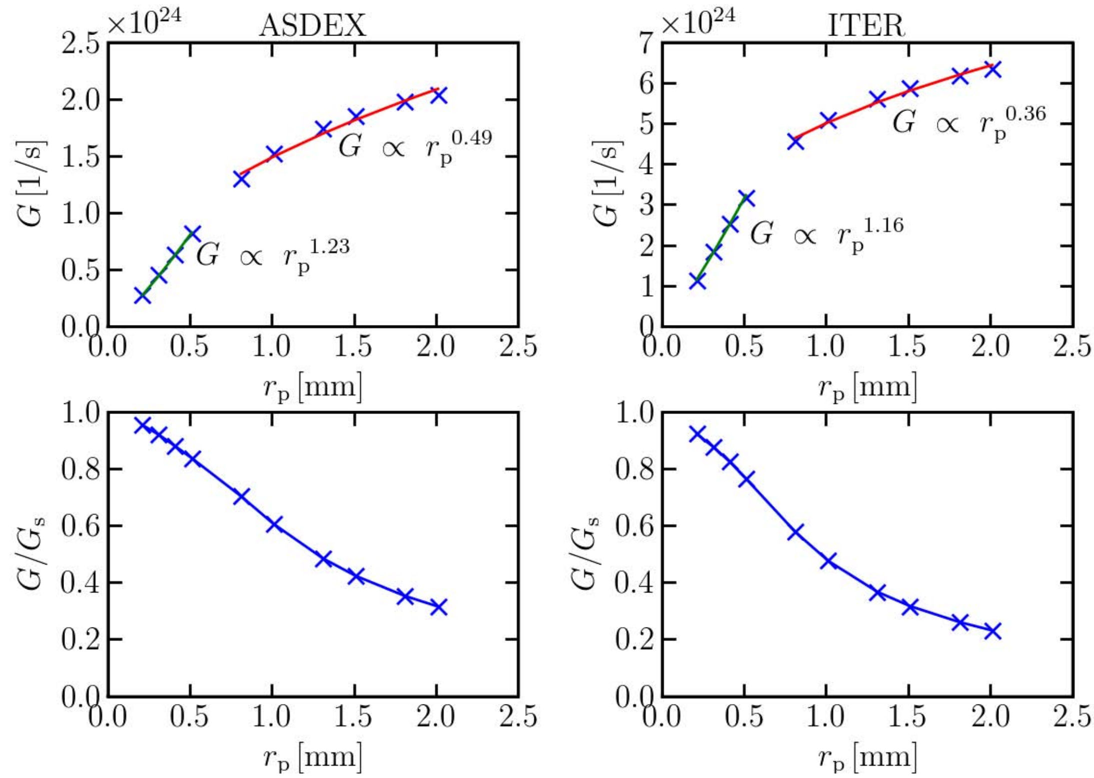

Figure 2: Ablation rates (G) and ablation rates compared to the corresponding spherical symmetric expansion (G_s) at different pellet sizes for the two model scenarios.

simulation at the same time our model is much more simple, therfore the quasi two-dimensional appellation is appropriate.

The dependence of the ablation rates on the model, pellet and plasmaparameters was examined in detail. It was found the the spherical symmetric scaling law is applicable at the current pellet injection experiments, but a significant deviation from that is expected at future experiments with larger pellets involved. This is caused by a dramatic change in the flow pattern and therefore in the shielding properties of the cloud, as well.

References

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