Pellet Ablation in Tokamak Reactors

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Abstract. Injecting frozen hydrogen pellets has been proposed as a method of efficiently refueling Tokamak fusion reactors. The intense heat of the reactor causes the pellet to lose mass in a process called ablation. This process creates a cloud-like area around the pellet which partially shields it from further ablation. We are interested in modelling the behavior of the pellet and the resulting flow numerically. We will present the effect of physical parameters such as magnetic field strength, pellet rotation, and pellet surface conditions on the rate of pellet ablation. Improvements made to older models will be discussed. Data and conclusion will be presented for the one-dimensional and two-dimensional case. Areas of further research will be explained.

1. Introduction

A tokamak is a reactor designed to use magnetic fields to confine the hot plasma required for nuclear fusion to take place. Spherical pellets of frozen hydrogen are injected as a method of refueling the reactor, and electrons from the plasma impact on the pellet surface, heating it. This results in the surface ablating neutral molecules, which in time form a dense ablation cloud around the pellet, partially shielding it from the hot plasma. The main interest lies in studying the rate of ablation and shape and formation of the ablation cloud.

The equations governing the flow are the Euler equations, a system of partial differential equations (PDEs) with added electromagnetic terms. Rather than attempting to solve this problem analytically, we have focused on understanding how the solution of these equations behave when solved numerically.

The "neutral gas shielding" (NGS) model has a simplified equation of state and heat deposition and ignores the effects of the magnetic field. This simplifcation allows us to more thoroughly understand the underlying behavior of the system of equations and implement numerical methods that calculate a solution much faster. It has also led to the production of several scaling laws for the variables of interest [1]. It is of some interest to understand how the data behaves when this NGS model's equations are solved using a lower-order PDE solver.

In the two-dimensional case, we implement a method that explicitly tracks the interface between the solid hydrogen pellet and the ablated material. This allows us to analyze the shape of the pellet as well as calculate the ablation rate with more accuracy. Samulyak, Lu and Parks [2] used this "front-tracking" method to introduce the effects of the magnetic field. Additionally, older models [3] utilized a nonuniform heat deposition on the pellet surface, resulting in a "pancake" shaped pellet, and neglected the effects of rotation of the ablation cloud.

2. Discussion

We have first attempted to recreate previous 1D NGS simulations using lower-order PDE solvers. Lower-order solvers have the advantages of computational speed and ease of implementation and analysis at the cost of accuracy. One major difficulty in this implementation has been numerical diffusion, the tendency of lower order solvers to average data, which incorrectly smooths out large gradients in density and pressure near the pellet surface [4]. As a result, the use of lower-order solvers to obtain a steady-state in this model has been elusive. One solution may lie in the use of Discontinuous Galerkin Finite Element Methods (DG-FEM), which represent the solution of the PDE on each grid element as a linear combination of orthogonal polynomials [5]. The solution is not required to be continuous across elements, which could allow us to resolve the enormous density and pressure gradient near the pellet surface.

On the other hand, the 2D MHD data was generated using the FronTier package, a collection of code designed to numerically solve the PDE of interest. This package utilizes a front-tracking method to explicitly keep track of the interface between the ablation cloud and the solid pellet by first propogating the interface and then updating the interior states. This allows us to implement the appropriate boundary conditions on the surface of the pellet with ease.

The presence of the magnetic field also affects the cloud shape and ablation rate. "Charging" on the boundary results in the rotation of the ablation cloud. [6]. The addition of the Lorentz force from the magnetic field causes an "ablation channel" to develop. The more powerful the magnetic field, the more narrow the channel, which in turn results in a lower ablation rate. Another major modification made to FronTier concerns the heat deposition on the pellet surface. In older models, this deposition was not uniform, which eventually resulted in a "pancake" shaped pellet after some time. In reality, the pellet is tumbling as it enters the tokamok, so its shape should remain spherical. The results can be seen in Figure 1. This modification results in a slightly wider ablation cloud than previous models.

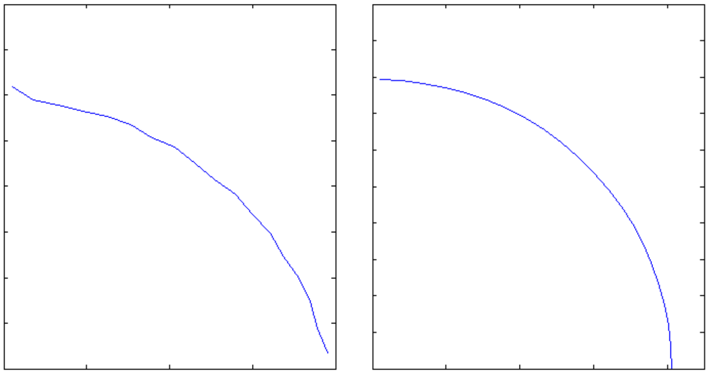

Figure 1. Comparison of pellet shape for non-tumbling pellet (left) and tumbling pellet (right).

3. Conclusions

We have developed both 1D and 2D numerical simulation of pellet ablation in tokamak fusion reactors. Our 1D work has led us to consider a new class of numerical solvers. Our 2D work has provided a more in-depth understanding of the effects of pellet tumbling, magnetic field strength, and cloud rotation on the ablation rate and cloud shape.

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