Study of NGS Pellet Ablation Rate in ITER Based on Two Different Pellet Ablation Rate Models Using 1.5D BALDUR Code

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Abstract

This research aims to study the pellet ablation rate, the pellet penetration, and the behavior of plasma during pellet injection in ITER using 1.5D BALDUR integrated predictive modeling code based on the Neutral Gas Shielding (NGS) pellet ablation rate concept. For this steady transonic-flow pellet ablation model, several extensions and modifications have been made over the years. For the development by P.B. Parks and R.J. Tumbull [Parks P.B. and Turnbull R.J., Phys. Fluids Vol. 21, pp.1735,1978], the actual Maxwellian distribution function of the incident plasma electrons is approximated by an equivalent monoenergetic distribution having the same heat flux and particle density. This model uses an equivalent spherically symmetric or isotropic heat source to approximate the electronic energy deposition. However, the incident plasma electrons are constrained to follow the straight magnetic field lines in tight helices, so that spherical symmetry is broken. The pellet ablation therefore involves at least a 2D geometry and a 1D geometry, used in the construction of the isotropic heating approximation for both the monoenergetic and spherically symmetric approximations, and are partially removed by B.V. Kuteev [Kuteev, B.V., Nuclear Fusion Vol. 35, pp.431,1995], who uses the actual Maxwellian distribution for the incident electrons, and attempted to account for the heating asymmetry imposed by the magnetic field. Park's model is well supported by experimentally measured pellets. In this work, the two development pellet ablation models, based on the NGS concept are implemented in BALDUR code to study the behavior of pellets during injection into the hot plasma. The result shows that the plasma temperature T_e decreased after pellet injection due to the low temperature of pellets and the plasma density n_e increased due to mass of pellets. The shapes of ablation rate profiles are quite different. The ablation rate given by the Kuteev model is approximately two times higher than the Park model, and declines steeply during the final stage. The areas covered by the two ablation rate curves are strictly the same. This corresponds to the fact that the total particle number conservation should be kept no matter what ablation model is used in the calculations, for the same pellet and the same plasma.

Keywords: Pellet fueling; Plasma; Tokamak; ITER; Ablation

1. Introduction

The injection of deuterium pellets into fusion plasmas has recently gained great importance due to at least two reasons. First, pellets are considered to be suitable for fueling of reactor plasmas, and, second, pellets are used to mitigate the Edge Localized Modes (ELMs) and thus reduce the power load on the divertors. To fully understand the mechanisms of these processes, the proper knowledge of the profile of the material deposited by pellets and thus the ablation rate is of crucial importance.

The interaction of pellets with hot magnetized plasmas is a complex 3D process phenomenon. Its description is from the solution of partial differential equations in 3D and in toroidal geometry together with the solution of the atomic physical rate equations, radiation transfer, and so on. To reduce the complexity to a computationally bearable level, simplifications have to be done. The first and nowadays still widely used approximation for ablation rate calculations is the Neutral Gas Shielding (NGS) model [1]. In this approximation the pellet is surrounded by its neutral, quasi steady state spherically expanding cloud. This neutral cloud shields the ambient background plasma, and the ablation rate is calculated by taking this shielding into account. The NGS model was several times further developed by including various phenomena, e.g. electrostatic shielding, atomic physical processes, and geometrical effects [2, 3].

In this work, the pellet ablation rate is investigated using a 1.5D BALDUR integrated predictive modeling code. In these simulations, the behavior of a pellet in the plasma is described using two different NGS models. This paper is organized as follows: brief descriptions of the BALDUR code are presented in Section 2; the details of the NGS pellet ablation model is presented in Section 3; the predictions of ITER for standard type I ELMy H-mode with pellet injection are described in Section 4; and the conclusion is given in Section 5.

2. BALDUR code

BALDUR is a language code that was written in FORTRAN. It is a 1.5 dimensional (a radial direction together with flux surface average) transport code designed to simulate a wide variety of plasma conditions in tokamaks. The BALDUR code follows the time evolution of electron and ion temperatures, charged particle densities (up to two hydrogenic species and up to four impurity species), and the poloidal magnetic flux density, as a function of magnetic flux surface. The shapes of the flux surfaces are determined by solving axisymmetric equilibrium force balance equations, given that boundary conditions may be changing with time. BALDUR provides a detailed and self-consistent treatment of neutral hydrogen and impurity transport (influxing neutrals from the wall as well as internal sources), multi-species effects (including an extensive atomic physics package), several forms of auxiliary heating (NBI and prescribed profile), fast alpha particles and fusion heating, plasma compression effects, ripple losses, and scrape-off-layer. There are a wide variety of transport models available. (Here, the theory-based Multi-Mode model is used) In addition, there are various options available to treat the axisymmetric effects of large scale instabilities such as sawtooth oscillations, saturated tearing modes, and high-n ballooning modes.

3. NGS ablation model

Two typical NGS scaling laws for ablation rate have been implemented in BALDUR code. One of the two models was developed by P. B. Parks in the 1970's, i.e. a one-dimensional approach with a monoenergetic electron heat flux model, based on the steady state approximations, and on the assumption of spherically symmetric hydrodynamic expansion, which results in the following formula [1]:

$$\frac{dN}{dt} = 1.12\times10^{16} n_e^{0.333} T_e^{1.64} r_p^{1.333} M_i^{-0.333} \qquad (1)$$

The other is the B.V. Kuteev model, i.e. a two-dimensional approach with electron and ion ablation including energy distribution effects (Maxwellian) and the pellet shape modification during ablation taken into account, and the scaling law is given below [7]:

$$\frac{dN}{dt} = 3.465\times10^{14} n_e^{0.453} T_e^{1.72} r_p^{1.443} M_i^{-0.283} \qquad (2)$$

In Eqs. (1) and (2), dN/dt is the ablation rate in atoms/s, n_e , T_e are the electron density in cm^{-3} and temperature in eV, respectively, r_p is the pellet radius in cm and M_i is the mass of the pellet material in atomic units.

4. Results and Discussions

The ablation rate using the two models were calculated by BALDUR code. Figure1 shows that calculation using the Kuteev model, which uses a Maxwellian distribution of electrons from the back-ground plasma, yields a higher ablation rate than that using the Parks model, which uses a monoenergetic electrons at (3/2),T_e. This is due to *1/E* dependence of the electron stopping cross-section above 1 keV [4]. The pellet penetration of the Kuteev model is lower than the Parks model and the distance between two peak locations is approximately 18 cm, the ablation rates in the peak position differ by approximately 15%.

The electron temperature decreased due to the low temperature of pellet and the electron density increased due to the mass of pellet, when pellet is injected. The result shows that the two models agreed well (see Figure 2, 3, 4, 5), but the shapes of ablation rate profiles are quite different. The ablation rate given by the Kuteev model is two times higher than that given by the Parks model and declines steeply during the final stage. But the areas covered by the two ablation rate curves are strictly the same. This corresponds to the fact that the total particle number should be conserved no matter what ablation model is used in the calculations for the same pellet and the same plasma.

Note that the Parks model is well supported by experimentally measured pellet lifetimes, but this is partly the result of a fortuitous cancellation [2, 8]. The question is why the improved models of Kuteev have an ablation rate that is a factor of two higher than that of experiments [3].

One possibility is due to the electrostatic shielding provided by the negatively charged pellet cloud, which would effectively reduce the incident electron density $n_{e\infty}$ and heat flux ($\sim T_{e\infty}$) by the Boltzmann factor $e^{-e\varphi/T_{e\infty}}$, where $T_{e\infty}$ is the plasma electron temperature, and the normalized potential drop [10, 11] across the cold cloud/hot plasma interface is $e\varphi / T_{e\infty} \approx$ 1.8 – 2.0. Hence the ''flux-limiter''

f appropriate for pellet ablation is $e^{1.8}$ to e^{2} or 0.135 – 0.165. The Boltzmann correction to the density and heat flux is only relevant for a Maxwellian distribution for which the normalized energy distribution function is *not* altered by a potential drop. Since the ablation rate scales with $n_{e\infty}^{1/3}$, the ablation rate would simply be reduced by a factor $e^{-e\varphi/3T_{e\infty}} \approx 0.51 - 0.55$, which could alone explain the factor of approximately 2 discrepancy. Similarly, the pellet surface pressure $\propto n_{e\infty}^{2/3}$ would be reduced by $e^{-2e\varphi/3T_{e\infty}} \approx 0.26 - 0.30$. A direct extension of the Parks model, including incident Maxwellian electrons, the geometrical effect of their heat deposition, and the above electrostatic correction, predicts for a pellet of radius r_p the mass ablation rate [9]:

$$G = \frac{1.36\times10^{-8} A^{2/3} r_p^{4/3} n_{e\infty}^{1/3} T_{e\infty}^{11/6}}{[\ln(2T_{e\infty}/I_*)]^{2/3}}\, g/s \qquad (3)$$

where A is the atom mass in amu (A =2.014 for deuterium pellets), I_* = 7.5 eV is the mean excitation energy of hydrogenic atoms, $T_{e\infty}$ and $n_{e\infty}$ are the plasma parameters, and cgs eV units are used. The numerical value of the ablation constant represents a synthesis of refinements and modifications contributed by other published papers, and it includes an order unity multiplier to eliminate the small discrepancy with the experimental ablation rate inferred from the multi-machine International Pellet Ablation Database IPADBASE of measured pellet lifetimes [9].

Pellet injectors usually produce cubic or cylindrical pellets. Such pellets are likely to become nearly spherical early on because a passage through the guide tube and/or ablation into the plasma quickly smoothes out irregularities such as edges and corners. In modeling ablation, the usual practice is to use the radius of an equivalent equal-mass spherical pellet, i.e., r_p =(3/16)$^{1/3}$. D is used in the case of a right circular cylinder pellet with length L equal to diameter D. This adjusted definition of r_p is understood for the pellet data archived in IPADBASE.To convert from G to dN/dt (atoms/s) one can use $dN/dt = N_A G/A$, where N_A is Avogadro's number.

5. Conclusion

In summary, it can be seen that pellet injection allows efficient particle refueling of hot plasmas relevant for next generation fusion experiments. The result shows that the plasma temperature T_e decreased after pellet injection due to the low temperature of pellet and n_e increased due to mass of pellet. The shapes of ablation rate profiles calculated using the Kuteev model and the Parks model are quite different. The ablation rate given by the Kuteev model is approximately two times higher than that given by the Parks model and declines steeply during the final stage. The areas covered by the two ablation rate curves are strictly the same. This corresponds to the fact that the total particle number conservation should hold true no matter what ablation model is used in the calculations for the same pellet and the same plasma.

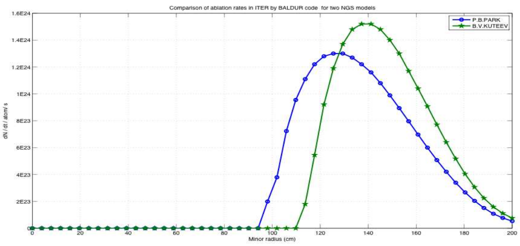

Fig 1. Comparison of the two NGS ablation rate profiles

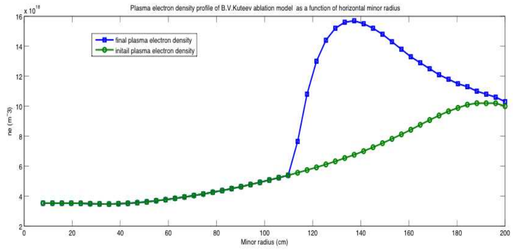

Fig 2. Plasma electron density increase after pellet injection (Kuteev model).

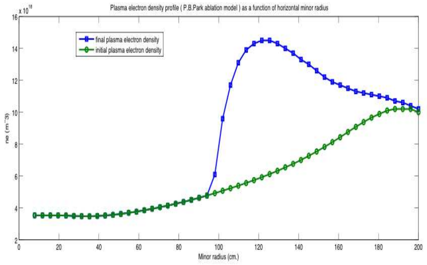

Fig 3. Plasma electron density increase after pellet injection (Parks model).

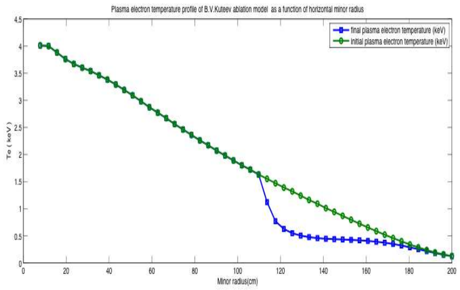

Fig 4. Plasma electron temperature decrease after pellet injection (Kuteev model).

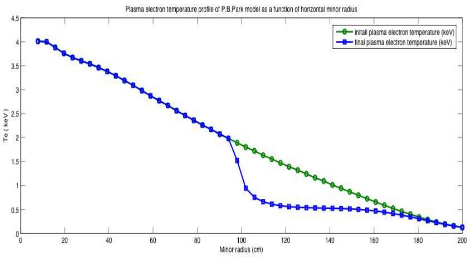

Fig 5. Plasma electron temperature decrease after pellet injection (Parks model).

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