Two-fluid MHD simulation of confinement of pellet-produced hydrogen clouds in hot magnetized plasmas

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The structure of dense particle clouds surrounding ablating hydrogen isotope pellets is investigated, with particular emphasis on the B-perpendicular expansion, ionization, and deceleration dynamics. A time-dependent single-temperature two-fluid 1.5-D Lagrangian model is used in which the neutral and ionized fluid components are allowed to move with different velocities.

As is well known, the H_α and H_β emission patterns of excited neutrals residing in hydrogen pellet clouds are cigar-shaped, elongated in the direction of the magnetic field lines (see, for example, Durst [1]), although the expansion of the neutrals is not affected by the presence of magnetic fields. Accurate determination of the confinement radii of pellet clouds is of relevance from the point of view of up-to-date pellet ablation models, in which the magnetic constriction of the cloud expansion plays an important role [2,3,4]. The objective of the present work was to obtain quantitative information on the magnitude of collisional coupling between the neutral and ionized species of pellet clouds and on some phenomena not considered in previous cloud studies such as the inductive electric field associated with the time variation of the magnetic field during the high-beta cloud expansion phase. The analyses available on pellet cloud evolution and pellet cloud properties, with magnetic field effects properly taken into account, are usually based on single-velocity approximations [3,4,5,6,7,8] and therefore yield no information on the magnitude of collisional effects. For this reason, a time-dependent two-fluid single-temperature Lagrangian MHD model was developed in which the neutral and ionized components are allowed to move with different velocities but are collisionally coupled. The cloud is heated by the background plasma: the energy input along the magnetic field lines is specified in terms of the thermal energy flux carried by the plasma electrons (with a flux-limiting factor of 0.50), and by anomalous heat conduction in the **B**-perp direction ($\chi_e = 1\ \mathrm{m}^2/\mathrm{s}$ was assumed). The ablated particles are released as neutrals, their ionization being followed up by finite-rate calculations. The model is based on the usual MHD conservation equations, Maxwell's equations, and various rate equations. The details can be found elsewhere [9].

With respect to the geometry and scenario considered, the fact that the ablated particles leaving the pellet surface expand with a velocity that is about an order of magnitude larger than typical pellet flight-velocities (10^4 m/s compared with 10^3 m/s) [10] offers a convenient way of analysis: the pellet velocity is ignored and the analysis is carried out in a cylindrically symmetric, stationary coordinate system whose axis is aligned with the magnetic field. A disc-shaped mass-source of infinitesimal thickness is placed at the centre, which represents the ablating pellet. The size (radius) and the strength of the mass-source are given. The space is filled with a homogeneous hot background plasma of given temperature and density. At time = 0 the mass-source is turned on and cold neutral particles are blown into the plasma at a given rate and continuously heated by the incident hot particles. The evolution of the cloud forming around the mass-source is followed up by numerical means. The Lagrangian cells (coaxial annuli) receive cold neutral particles as long as they are in contact with the source. The cell boundaries are propagated in the radial direction with the particular velocity at which the neutral particle flux crossing the boundary from one side is balanced by the ion flux coming from the other side, the absolute value of the ion velocity being, in general, smaller than or equal to the neutral velocity. Hence at each cell interface one has

$$n_a\left(v_{ar} - v_r\right) + n_i\left(v_{ir} - v_r\right) = 0$$

where v_{ar} and v_{ir} are the radial velocities of the neutral and ionized components, computed by solving the respective momentum equations, and v_r represents the velocity of the cell boundary considered. Defining the degree of ionization α as $\alpha \equiv n_i/\left(n_a + n_i\right)$, the grid velocity can readily be expressed as a weighted function of the ion and neutral velocities:

$$v_r = \alpha\, v_{ir} + (1-\alpha) v_{ar}.$$

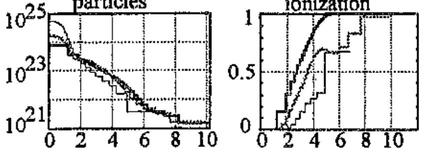
As can be seen, in the case of fully ionized and/or neutral clouds, the radial component of the grid velocity converges to the velocities of the ionized and/or neutral components, respectively.

In the axial (field-aligned) direction, it is assumed that, due to sufficiently high collisionality, the neutral and ionized species move with the same velocity: $v_{az} = v_{iz} = v_z$. The axial expansion velocity is calculated in terms of the cloud - background plasma pressure difference affecting the **B**-perp interface of each annular cell. To assure approximately equal cell masses, the number of cells can be increased during the computations. Artificial viscosity is used, if needed, in the numerical scheme. The input parameters of the model thus defined are T_{e0}, n_{e0}, B_0, size and strength of the mass-source (pellet radius and ablation rate), respectively.

Scenario calculations were performed with systematic variation of the input parameters. In the following, some representative results are described.

In FIG.1, the radial distributions of some cloud parameters (heavy-particle density in m^{-3} (a), ionization degree (b), temperature in K(c), Mach number of the radial expansion

velocity (d)) are given for the following set of input parameters:
$n_{e0} = 5\cdot 10^{19}\,\mathrm{m}^{-3}$; $T_{e0} = 500\,\mathrm{eV}$; $B_0 = 2\,\mathrm{T}$; $\dot{n}_s = 2\cdot 10^{23}\,\mathrm{s}^{-1}$; $r_s = 1\,\mathrm{mm}$


(a) Density of heavy particles (b) Degree of ionization

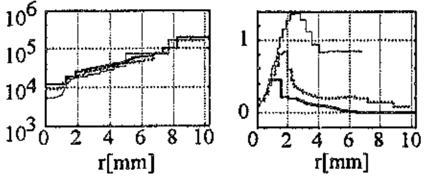

(c) Temperature (d) Mach-number

FIG.1.

The three curves shown correspond to three different time levels: 0.3 µs (thin solid line), 0.6 µs (dotted line), and 0.9 µs (heavy solid line). (The horizontal sections of the curves represent the thickness of the Lagrangian cells.) The asymptotic radial flow pattern is inherently subsonic, in disagreement with earlier steady-state transonic neutral shielding ablation models [11,12].

Since the radial expansion of the ionized matter is first stopped at the periphery and this deceleration 'wave' propagates from the periphery into the cloud interior, the effective channel cross-section for the axial (**B**-parallel) momentum transfer defined by the ratio of the volume integrals $R_{\mathrm{eff}} = \int r\cdot v_z(\rho_a+\rho_i)\,dV \;/\; \int v_z(\rho_a+\rho_i)\,dV$ may change in time. For the scenario shown in FIG.1 the asymptotic value of the 'effective radius' $R_{\mathrm{eff}}(\tau \geq 10\,\mu\mathrm{s})$ is about 68% of its initial (maximum) value. The constricted flow of the ablated material in channels whose effective cross-sections are less than those defined by the respective confinement radii may be responsible for the striated structure of pellet wakes observed in tokamaks [10].

At the beginning of the ionization process, the neutral fluid component may move significantly faster than the ionized component. In FIG.2, the specific radial momenta of the two components (given in $\mathrm{kg\cdot m^{-2}\cdot s^{-1}}$) are plotted as functions of the radius at two time levels: 0.3 µs and 20 µs.

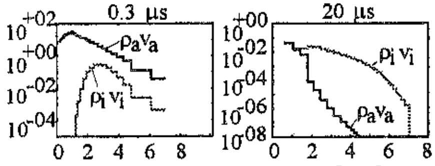


FIG.2.

As can be seen, prior to substantial ionization, the momentum of the neutral component significantly exceeds the ion momentum. During a time interval comparable to the residence time of the pellet in its own magnetically confined cloud, the neutrals lose practically all their radial momentum because of collisions with ions (except in a small region adjacent to the neutral source).

With regard to the effect of the inductive E-field on the cloud evolution, different approximations were used for calculating the $\mathbf{j}\times\mathbf{B}$ force appearing in the momentum equation [9].

With regard to the confinement radius, numerous scenario calculations were carried out with systematic variation of the input parameters [9]. At low plasma temperatures, the radial extension of the cloud is determined primarily by the ionizaton time: an increase of the input plasma temperature causes a decrease of $R_{99\%}$ (99 % mass, low-temperature regime: LTR). At high plasma temperatures, $R_{99\%}$ is controlled by the internal pressure evolving in the cloud: typical high-beta interaction takes place. The pressure is able to push the ionized outermost layer of the cloud outward against the $\mathbf{j} \times \mathbf{B}$ force. In this case an increase in the plasma temperature is associated with a corresponding increase in $R_{99\%}$ ($\dot{n}_s$ and B_0 are kept constant, high temperature regime: HTR). Unlike $R_{99\%}$, the ionization radius (the outermost radius where $\alpha = 0.99$) was found to be a monotonic function of T_{e0}. The cloud radius was found to be proportional to $B_0^{-1/6}$ in LTR and proportional to $B_0^{-1/2}$ in HTR ($\dot{n}_s, T_{e0}$ constant). Another power-law dependence of $R_{99\%}$ on the ablation rate ($\dot{n}_s$) was found to be $R_{99\%} \propto \dot{n}_s^{1/3}$ in LTR and $R_{99\%} \propto \dot{n}_s^{1/4}$ in HTR.

Concerning the calculated confinement radii, good agreement was found between the present results and some experimental measurements [9]. There is reasonably good agreement between the results obtained with the present two-fluid model and those stemming from simpler approximations: single-cell Lagrangian model [4], or multi-cell single-fluid model [3]. The two-fluid model consistently calculates stopping radii somewhat larger than the above approximations. On the other hand, the ionization radii computed with the present model are very close to the confinement radii of the other models. At higher plasma densities, the calculated values of the ionization radius, electron density, cloud temperature, etc., agree well with experimental observations in the case of both two-fluid and single-fluid models. Further checks against experimental data, particularly in the low plasma density domain, are needed.

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