BURNING ANALYSIS OF ITER-LIKE PLASMA BASED ON 0-DAND 1-D TRANSPORT MODELS

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1. Introduction

The attainment of the self-ignited state of plasma is one of the objects of next step fusion research. By using the theoretical model scaling law τ_E, which could explain the characteristics of the L-mode and the high β_p -mode, a point model has shown that there is an ignition window, which does not depend on H-mode [1]. It provides a backup scenario when the H-mode condition shall turn out to be difficult to satisfy. In this article, 1-D transport code is used to examine the impact of profile effect on the burning performance.

2. Model equations

We solve one dimensional energy transport, He-ash particle transport and poloidal magnetic field transport equations. Here we assume that temperatures are the same values for all species and α-particles are fully thermalized without escaping from the plasma.

The energy transport equation is given by

$$\frac{\partial}{\partial t}\frac{3}{2}n_e(2-f_{He})T = \frac{1}{4}n_e^2 f_i^2 E_\alpha\langle\sigma\upsilon\rangle + \frac{1}{r}\frac{\partial}{\partial r}rn_e(2-f_{He})\chi\frac{\partial T}{\partial r} + P_{OH} - P_{br}, \tag{1}$$

where the terms in R.H.S represent the power input from α-particles (with $E_\alpha = 3.52$ MeV, and $<\sigma\upsilon>$ indicates D-T fusion reaction rate), the heat transport losses, the ohmic heating term P_{OH}, and the volume power losses with bremsstrahlung P_{br}, respectively. The values f_{He} and f_i indicate the ratios of helium and ion densities to electron density, respectively. The value χ is a bulk thermal conductivity which is obtained from a combination of neoclassical diffusivity [2] and CDBM (current diffusive ballooning mode) diffusivity[3]. A test of this model χ for present experiments has been reported in [4]. The radiation loss is dominated by the bremsstrahlung. The particle balance of He-ash is given by

$$\frac{\partial}{\partial t}n_e f_{He} = \frac{1}{4}n_e^2 f_i^2\langle\sigma\upsilon\rangle + \frac{1}{r}\frac{\partial}{\partial r}rD_{He}\frac{\partial n_e f_{He}}{\partial r}, \tag{2}$$

where D_{He} is the particle diffusivity for He-ash. The ratio of χ and D_{He} i.e., $\rho \equiv \chi/D_{He}$ is introduced and assumed to be constant. The electron density profile is fixed as $n_e(r) = (n_{e0} - n_e(a))(1 - r^2/a^2)^\delta + n_e(a)$, where the value δ indicates the effect of density peaking. The poloidal field evolves according to

$$\frac{\partial}{\partial t}B_\theta = \frac{\partial}{\partial r}\eta_{NC}\left[\frac{1}{\mu_0}\frac{1}{r}\frac{\partial}{\partial r}rB_\theta - J_{BS}\right], \tag{3}$$

where η_{NC} is the neoclassical current diffusivity and the bootstrap current J_{BS}[2] is anticipated as a source term. Here, four parameters are considered, i.e., I_p^{tot} (total plasma current), $\langle n_e \rangle$ (volume averaged electron density), ρ (the ratio of thermal conductivity to He-ash diffusivity), and δ (peaking factor for the electron density profile).

3. Burning transport analysis

We evaluate the burning performance of D-T plasma using ITER-like parameters (R = 8.14 m, a = 2.8 m, B_t = 5.68 T, $I_p^{tot} = 20MA$, $\langle n_e \rangle = 10^{20}\,m^{-3}$ and $\delta = 0.5$)[5]. The edge density is chosen as $n_e(a) = 10^{19} m^{-3}$ and $T(a) = 50\,eV$. This means that the boundary condition of L-mode is employed and the burning state does not rely on H-mode.

Figure 1 shows profiles of temperature, heating and thermal diffusivity at the early phase of burning state ($t = 25$ sec), where the $J(r)$-profile is given as $J(r) \propto 1 - (r/a)^2$ and $q(0) \simeq 1.5$. In this state, the temperature and He density reach their quasi-stationary state, and fusion output is $P_f = 3.7\,GW$. This figure indicates that if we choose $q(0) \simeq 1.5$ for a target current profile, an internal transport barrier is formed autonomously and the self-ignition is sustained within the time scale of burn-time even if parameters lie in L-mode boundary condition. If we calculate the burning performance using 0-D model, $\langle T \rangle \sim 25\,keV$ is obtained for $\langle n_e \rangle = 1.0 \times 10^{20}\,m^{-3}$, $I_p^{tot} = 20\,MA$ and $\tau_{He}/\tau_E = 11.0$ (see Fig. 8 in Ref. [1]).

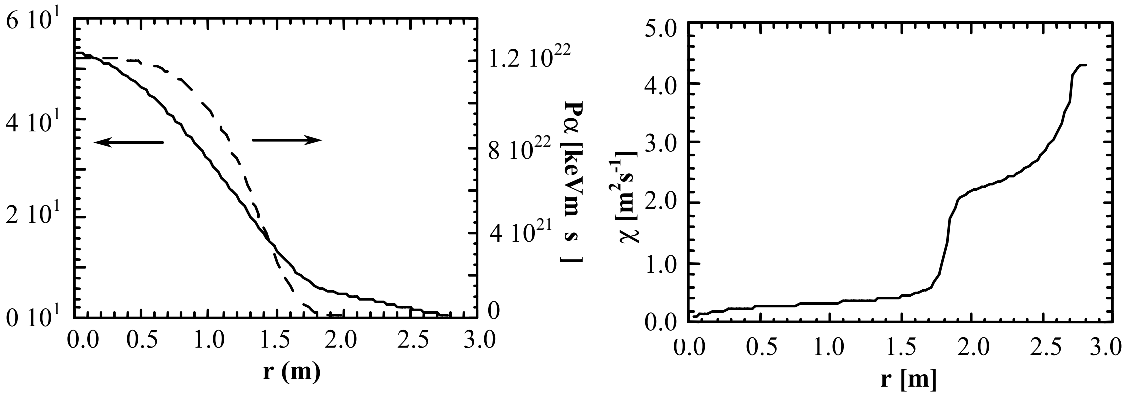

Figure 1. Profiles of temperature, α-heating and thermal diffusivity at the early phase.

Figure 2 shows the self-ignition condition in $\langle n_e\rangle - \langle T\rangle$ phase space at $t = 25\,\sec$. The cases with ρ = *3,7,11* and δ = *0.5, 3.0* are plotted. Two kinds of solutions appear. One is quenched solution where the plasma does not ignite. The other is ignited solutions $\left(\langle T\rangle > 10keV\right)$ where α-heating is dominant. It is confirmed that for ρ > *13,* only quenched solutions appear. There is a threshold value of $\langle n_e\rangle$ above which the ignited solutions appear. The dotted line indicates Greenwald density limit [6] ($\langle n_e\rangle^{GW} = 8.0 \times 10^{19}\ m^{-3}$). This result shows that the sensitivity of the ignition condition on $\langle n_e\rangle$ is strong and there is no margin of self-ignition for the density limit when density profile is flat. However, if we choose a higher value of δ, solutions that satisfy the density limit exist. Profile control is crucial to access the region above density limit; Pellet injection is considered to be an effective method shown by ASDEX-U experiments [7]. This point is important issue for future research.

In the time scale of current diffusion L/R, $J(r)$ starts to peak in the central region and finally the internal transport barrier disappears. Under this slow change of $J(r)$, nevertheless, the self-ignition state is still maintained with L-mode boundary condition. If we do not impose any constraint for $q(0)$, the concentration of current in the central region will continue and attain the level of $q(0) \sim 0.3$, so that MHD stability could be a serious problem. This result implies that the sustainment of burning state in this scenario has the issue of stability after the burn is ignited, but not of confinement as long as the control of $n_e(r)$ is possible.

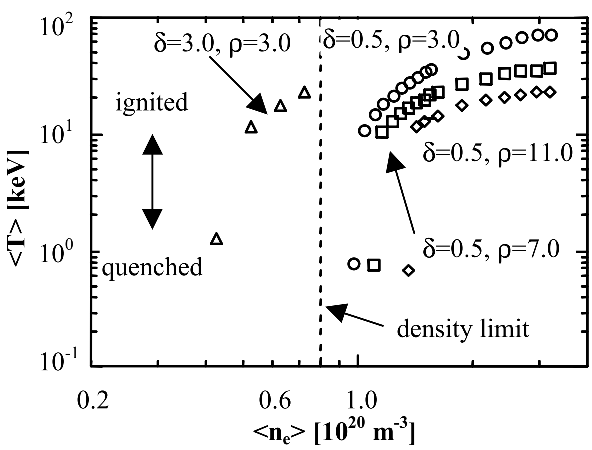

Figure 2. Self-ignition condition in <ne> - <T> phase space at the early phase.

Figure 3(a) shows the self-ignition condition in $\langle n_e\rangle - \langle T\rangle$ phase space at the steady state $(t \sim L/R \sim 1000)$, where $q(0) \sim 0.3$ holds. Quantitatively, $\langle T\rangle$ is about half times as large as that at the early phase, where $q(0) \simeq 1.5$ holds, but the ignition condition is sustained. The importance of the density profile is illustrated in Fig.3(b). The dependence of power output on δ for various values of ρ is shown satisfying the density limit, $\langle n_e\rangle = 8.0 \times 10^{19}\ m^{-3}$. As the He confinement becomes better, stronger peaking is required.

Cases of low current are also studied. If the current is reduced at the level $I_p^{tot} \simeq 10MA$, the self-ignited state will be sustained by the internal transport barrier (so-called 'high β_p mode operation'), however it is difficult to satisfy the condition of β-limit in this case.

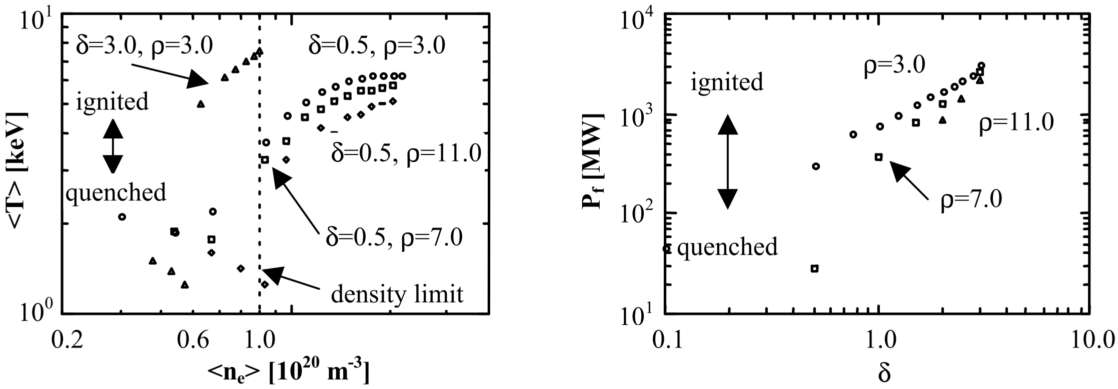

Figure 3. (a) Self -ignition condition in <ne> - <T> phase space at the steady state.
(b) Dependence of fusion output on density peaking at the steady state.

4. Summary and discussion

The burning performance is evaluated based on 1-D transport model for the ITER-like plasma. Ignited solutions are obtained even in the case of the L-mode boundary condition. Long sustainment of ignition is also shown. The density profile control is crucial for a burning scenario, which could be a backup to the scenario utilizing the H-mode.

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