Burning fraction, radial transport, and steady state profiles of multi-species particles in CFETR burning plasmas

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Received 10 December 2019, revised 30 March 2020
Accepted for publication 23 April 2020
Published 28 May 2020

Abstract

The burning fraction of fuel particles is a crucial issue for future fusion reactors. In order to achieve the high tritium burning fraction required by China Fusion Engineering Test Reactor (CFETR) engineering design, fueling depths and quantities should be estimated by particle control analysis for different scenarios. Thus, in this paper, a multi-species fluid model of deuterium-tritium (D-T) fusion plasmas is applied to study radial transport and profile evolution with CFETR parameters under different fueling conditions. In the model, alpha particles are treated with a slowing down model and diffusion coefficients are introduced according to $\tau_{\text{E}_98}$. Then, in such a self-consistent burning plasma simulation, the results show that the fusion reaction and fueling parameters effect remarkably changes the shape of D/T profiles, while to alphas and helium ash however, the effect of the fueling parameters is much weaker. It is also seen that the burning fraction is increased substantially with the fueling depth, and significantly affected by particle confinement. Furthermore, by substantially raising the D:T ratio to the regime of above unity, the burning fraction can be increased notably, but with a cost of a certain level of fusion power reduction.

Keywords: CFETR, D-T fusion plasma, tritium burning fraction

(Some figures may appear in colour only in the online journal)

1. Introduction

For the next generation of fusion reactors, such as China Fusion Engineering Test Reactor (CFETR), particle control is a key issue to be addressed. With significant fueling and ash removal due to GW fusion power and high burning fraction, sustaining preferred particle distribution profiles for various scenarios is a great challenge for steady state operation [1].

One of the most crucial issues in CFETR engineering design is the requirement for the fueling system. Different from previous tokamaks, the aim of CFETR is to achieve the steady-state burning plasma with possible tritium self-sustaining [2]. Abdou et al [3] proposed a model of the fuel cycle for D-T fusion reactors and pointed out that raising the burning fraction would effectively ease the requirement of Tritium breeding ratio (TBR). The figure 1 illustrate the fuel cycle in detail. As the D-T mixture pellets are fueled into the plasma, some of them participate in the D-T fusion reaction and produce neutrons and alpha particles, and the rest will
be diffused and/or pumped out. While the neutrons provide the fusion power and the tritium breeding source, the alpha particles slow down or even thermalized to helium ash to be removed. Through purification, both of reproduced and recycled tritium particles are deposited in tritium repository for pellet injection. This fuel cycle directly relates the fueling condition with TBR and fusion performance, as shown in figure 1.

According to the definition of burning fraction, the ratio of burned to total tritium particles, the fueling condition is directly related to the fusion performance. By separating effects of edge and central NBI fueling contributions in JT-60 experiments, Takenaga et al [4] found that the confinement time of centrally fueled particles was about 3 times longer than that of edge fueled particles. Nevertheless, since significant NBI central fueling in CFETR is hardly to be realized, we thus in this paper refer the central fueling to the pellet injection. The fuel depth effect on ITER fusion performance was studied by Wang and Wang [5, 6]. Their results showed that even a small deviation of the fuel depth was able to make a remarkable difference, e.g. a 0.1 minor radius deeper led to a 61% improvement of the particle confinement as well as a fusion performance change of 108%.

Not only is the fueling system of a fusion reactor a measure to keep the steady state fusion reaction but also an implement for burning control and the requirement of TBR. As a D-T plasma starts to burn, substantial fusion reactions take place and a significant number of alpha particles is generated and then slowed down to helium ash. Then the plasma enters a multi-species state totally different from the original burning-free state. Guazzotto and Betti [7] found that in such a multi-fluid situation, a higher Lawson product threshold was required for ignition than that in a single-fluid model. Also, Boyer et al [8] applied a zero-dimensional multi-species fluid model to study particle control for future fusion reactors with global fueling. Therefore, in order to make more precise prediction of operation scenario and control, it is necessary to consider a multi-fluid model with the burning plasma effect for the fuel system design of CFETR. Previously, the prediction for CFETR density profiles was made by TGYRO [9] under OMFIT framework [10] with the electron particle flux calculated by TGLF [11] in core plasmas and fixed density pedestal [12]. It nevertheless did not take burning effect and fuel system design consideration into account.

To address the issue of particle control in CFETR-like tokamaks, in this paper propose a multi-species fluid model of deuterium-tritium (D-T) fusion plasmas for radial transport and profile evolution. The related numerical code is then developed based on BOUT++. Tritium/deuterium, helium ash, and alpha particle density profiles under the different fueling cases are then shown in numerical simulations. Different fuel depth and quantity and the ratio of deuterium to tritium (D:T) are also tested to investigate the effects on the burning fraction.

The layout of the paper as follows. Basic equations of the model, settings of fueling profiles, and boundary conditions are listed and discussed in section 2. Numerical results of particle density profiles, as well as burning fraction and fusion power, with different fueling depth and quantity, and D:T are shown in section 3. Finally, the conclusion is summarized and discussed in section 4.

2. Numerical model

2.1. Basic equations

The multi-species fluid model for particle transport and profile evolution in burning plasmas includes five particle species (deuterium, tritium, helium ash, alphas and electrons), corresponding to \( n_D, n_T, n_\alpha, n_{He}, n_e \). For deuterium and tritium, regarded as background species, the fueling and burning loss will directly influence the density. Thus, the corresponding equations are written

\[
\frac{\partial n_D}{\partial t} + \nabla \cdot \Gamma_D = S_D - n_D n_T \langle \sigma_D v \rangle
\]

\[
\frac{\partial n_T}{\partial t} + \nabla \cdot \Gamma_T = S_T - n_D n_T \langle \sigma_T v \rangle
\]
where $\Gamma_D, \Gamma_T$ is the transport flux of deuterium and tritium, and $\langle \sigma_D \nu \rangle$ is the reaction rate of D-T fusion relying on temperature. The sources of $S_D$ and $S_T$ are assumed in the form of

$$S = S_0 e^{-\left(\frac{\psi - \psi_0}{w} \right)^2} \quad (3)$$

where $S_0$ is the amplitude of the fueling source, $\psi$ is the normalized poloidal flux, $\psi_0$ is the fueling deposition position, and $(w = 0.1)$ is the profile width of fueling.

Alphas are created by D-T fusion reaction and then slow down to helium ash. While it is a reasonable approximation for the helium ash, the fluid treatment is not a good assumption for alphas with a shell-like distribution in the velocity space. Nevertheless, following the slowing down discussions in reference [14, 15], we have the steady state relation of $S_\alpha = n_D\nu_T \langle \sigma_D \nu \rangle - \frac{\eta_\alpha}{\tau_{s\alpha}}$, where $\tau_{s\alpha}$ is the energy confinement time of alphas on the order of the slowing down time. Hereafter we then use the slowing down time to approximate the energy confinement time. Thus, one can assume a fluid-like treatment of the continuity for alphas

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot \Gamma_\alpha = n_D\nu_T \langle \sigma_D \nu \rangle - \frac{n_\alpha}{\tau_{s\alpha}} \quad (4)$$

where $\Gamma_\alpha$ is the particle transport flux of alphas. Then we also can use the relation to distinguish the helium ash from alphas by using the alphas loss due to energy dissipation, $\frac{\eta_\alpha}{\tau_{s\alpha}}$, as the source of the ash. Therefore, one can also have the continuity for the helium ash

$$\frac{\partial n_{He}}{\partial t} + \nabla \cdot \Gamma_{He} = \frac{n_\alpha}{\tau_{s\alpha}} \quad (5)$$

where $\Gamma_{He}$ is the particle transport flux of the helium ash.

According to the classical slowing down theory [16], which works pretty well in JET D-T fusion [17] and alpha slowing down experiments [18], the slowing down time can be expressed by:

$$\tau_{s\alpha} = \frac{\tau_{s\alpha}}{3} \ln \left( \frac{W^\alpha_{edge}}{W^\alpha_{s\alpha}} \right) + \frac{W^\alpha_{s\alpha}}{W^\alpha_{th\alpha}} + \frac{W^\alpha_{c\alpha}}{W^\alpha_{crit}}$$

$$\tau_{s\alpha} = \frac{0.2A_\alpha T^\alpha_{1.5} [keV]}{Z_0 n_\alpha [10^{20} m^{-3}]} \ln \Lambda$$

$$W_c = 14.8 Z^{2/3} \Lambda^{1/3} T_c$$

| Table 1. CFETR design parameters. |
|-------------------------------|
| Major radius $R(m)$ | Minor radius $a(m)$ | Toroidal field $B(T)$ | Plasma current $I_p(\text{MA})$ | Current drive power $P_d(MW)$ | Vertical elongation $\kappa$ |
|-------------------------------|
| 7.2 | 2.2 | 6.5 | 13.78 | 74 | 2.0 |

where $\tau_{s\alpha}$ is the electron-alpha slowing down time, $W_c$ is the critical energy, $T_{th\alpha}$ is the ion temperature, and $f_\alpha$ is the alpha particle energy distribution, with also $W_{ao}(=3.5 \text{ MeV}), A_\alpha(=4), Z_\alpha(=2)$ and $\Lambda$ are the initial energy, atomic mass, charge, and effective charge of alphas, respectively. Then the electron density can be determined by the quasi-neutral condition

$$n_e = n_D + n_T + 2n_{He} + 2n_\alpha \quad (10)$$

2.2. Boundary conditions and code development

To simplify the problem, the temperatures of these species are assumed to remain the same ($T_e = T_D = T_T = T_{He}$) in the simulation, with the central temperature slightly less than $30 \text{ keV}$ to avoid overestimates of fusion power and burning fraction. For boundary conditions, the Neumann condition is applied for all species in the core. On the edge however, we set

$$n_D|_{edge} = n_T|_{edge} = 5 \times 10^{18} m^{-3}, n_{He}|_{edge} = 5 \times 10^{17} m^{-3}, \text{ and } n_\alpha|_{edge} \approx 0 \quad (11)$$

2.3. Diffusion and pinch profiles

The particle flux in above basic equations for different species can be expressed

$$\Gamma_s = -D_s \nabla n_s + n_s V_s$$

where the subscript $s$ stands for different species, with the diffusion coefficient $D_s$, and the pinch velocity $V_s$. Clearly, in steady states without fusion reaction, the diffusion term $-D_s \nabla n_s$ should be balanced by the pinch term to maintain the profile. Both $D_s$ and $V_s$ can then be obtained by theory or experiments. In this simulation, we assume that in the radial direction, diffusion coefficient and pinch velocity for approximately thermalized species (D, T, He) have the form of

$$D_s(D) \propto D_\perp = D_{s\perp} = 0.1 \chi_s$$

where $\chi_s = \frac{2C_{e\alpha} \tilde{a}^2}{\tau_{e,98}} [0.25 + 0.75 \left( \frac{r}{a} \right)^4] F(r)$

$$F(r) = (1 - A) e^{-\left( \frac{r}{a} \right)^2} + A$$

$V_i = 2C_v \frac{r}{a} D_i$
Figure 2. Parameter profiles at initial used in this simulation: (a) the diffusion coefficient of D, T, subject to change with $\tau_E$; (b) the pinch velocity of D, T; (c) and (f) profiles of fueling (at $\psi_0 = 0.7$) and temperature; (d) and (e) diffusion coefficient and pinch velocity for alphas.

where $\chi_s$ is the heat conduction coefficient, and $a$ is the minor radius. Also, the same as in Corediv JT-60SA simulation [19], $A = 0.1, \psi_0 = 0.93, p = 20$, and adjustable parameters $C_{el} = 1, C_v = 0.65$. For the coordinates $(\psi, \theta, \xi)$ in BOUT++ framework, $\sqrt{\psi} = r$ is assumed. The pinch velocity is setting to be 0 at the edge to ensure no external fueling from outside. For the energy confinement time, one can use the well-known scaling form of \cite{17}

\[ \tau_{E,98} = 0.056 2^{0.93} B^{0.15} P^{-0.69} \pi^{0.41} \tilde{M}^{0.19} R^{1.97} \rho^{0.58} k^{0.78} \]  

(17)

Certain global CFETR parameters are shown in the table 1. Note that the average density $\tilde{n}$, the average atomic mass $\tilde{M}$, and the heating power $P$ will evolve with the simulation process, which directly affects the magnitude of the diffusion coefficient as shown in equation (14). And they are calculated consistently as

\[ \pi = \frac{\int_V n_J d\psi d\theta d\xi}{\int_V J d\psi d\theta d\xi} \]  

(18)

\[ \tilde{M} = \frac{\int_V 4n_\alpha + 4n_{He} + 2n_D + 3n_T J d\psi d\theta d\xi}{\int_V J d\psi d\theta d\xi} \]  

(19)

\[ P = P_{cd} + P_{\alpha} = P_{cd} + n_D n_T \langle \sigma_{DT} \rangle W_{\alpha 0} \]  

(20)

The diffusion and pinch of alphas is very different from the other species. While the fully kinetic treatment remains a great
challenge, we in this simulation use a simplified approach based on the quasilinear model by Angioni et al for study of micro-turbulent transport of alphas and helium ash [20]. With fitting the results of the gyrokinetic simulation, they found that the alpha particle diffusion and pinch can be expressed as

$$\Gamma_{\alpha}^{\alpha/TG/TEM} = -D_{\alpha}^{\alpha/TG/TEM} \frac{dn_{\alpha}}{dr} = n_{\alpha} D_{\alpha} \left[ \frac{1}{L_{\alpha}} + \frac{C_p}{R} \right]$$ (21)

$$D_{\alpha} = D_{He} \left[ 0.02 + 4.5 \left( \frac{T_e}{E_{\alpha}} \right)^2 + 350 \left( \frac{T_e}{E_{\alpha}} \right)^3 \right]$$ (22)

$$C_p = \frac{3}{2} \left( \frac{R}{E_{\alpha}} \right) \left\{ 1/[(1 + 1/W_{e})^{5}] \log(1 + 1/W_{e}^{1.5}) \right\}$$ (23)

where $L_{\alpha}$ and $L_{He}$ are the characteristic lengths of alpha particle density and electron temperature, respectively. The alpha particle pinch velocity is set to be 0 when very close to edge. To clearly describe the numerical model, the crucial profiles in the simulation, i.e. (a) the diffusion coefficient of D, T ions, (b) the pinch velocity of them, (c) the fueling (at $\psi_0 = 0.7$); (d) the diffusion coefficient of alphas; (e) pinch velocity of alphas and (f) the temperature of D, T, are shown in figure 2.

3. Simulation results

3.1. Particle density profiles of various species

As the first step of our simulation, we compare the variation of density profiles under different fuel conditions. Four different fuel depths at $\psi_0 = 0.3, 0.5, 0.7, 0.9$ in equation (3), and four different fuel quantities of $\int_0^{\psi_0} \int_0^{\pi} \int_0^{\xi} n_j s J_\alpha d\psi d\xi = 9.51 \times 10^{21}, 1.105 \times 10^{22}, 1.26 \times 10^{22}, 1.415 \times 10^{22}$, are used in this simulation. The ratio of deuterium to tritium is fixed as 1:1 in this subsection. Then the steady state density profiles corresponding to different fueling cases are shown in figure 3.

Comparing the results of figure 3 with fusion term $n_D n_T (\langle \sigma v \rangle)$ (the solid lines) in equations (1)–(2) and without it (the dashed lines), we can find that the fusion effect significantly re-shapes the density profiles. In the region of $\psi < \psi_0 = 0.4$, the density profile gets flattened due to the balance between fusion reaction and fueling. For a fixed fuel depth, i.e. the same color lines in figures 3(a)–(d), but with different fuel quantities, it is shown that the fuel quantity hardly affects the density profile shape, but only its magnitude. The more obvious effect is seen as the fuel position changes. The density is more significantly reduced as the fuel depth gets shallower, i.e. the fueling position $\psi_0$ moves out to the edge, from $\psi_0 = 0.3$ to $\psi_0 = 0.9$. For example, in the case of the fuel quantity of $9.51 \times 10^{21}$, as shown in figure 3(a), the density profile significantly re-shapes and becomes higher in the...
inner region and lower in the outer region when the fuel depth increases, i.e. the fueling position $\psi_0$ moves inwards.

The alphas density profiles approximately calculated by the conventional slowing down model are shown in figure 4. The profiles are similar to that measured in TFTR D-T fusion experiments [21], with a very sharp peak at the center due to the small alpha diffusion coefficient in that region, as figure 2(d) shown. Nevertheless, such simulation results are only an upper limit of alphas density, due to the fact that certain important losses of the alphas, particularly the noteworthy first orbit loss due to the kinetic effect [21], are not included in the model. With the fuel quantities rising from $9.51 \times 10^{21}$ to $1.415 \times 10^{22}$ at fixed fuel position, the magnitude of the central density is only changed by ~ 16%. However, when the fuel position $\psi_0$ change from 0.3 to 0.9, the magnitude of central density is changed almost 100%, which is consistent with the conclusion from figure 3 that the fuel depth strongly reshape the density of deuterium and tritium profile. The fraction of alphas is about 1.5%-3% of the D/T ions in the core, indicating a 3% burning fraction (with D:T = 1) under fueling conditions in the parameter regime of CFETR operations.

Helium ash density profiles in a steady state operation under corresponding fueling conditions are shown in figure 5. Unlike the D/T density profiles, the shape of the helium ash profile is not changed much as the fueling depth varies. A larger transport coefficient makes the helium ash density consistently higher as the fuel position $\psi_0$ increases from 0.3 to 0.9, i.e. the fueling depth ($= 1 - \psi_0$) decreases from 0.7 to 0.1, which is quite different from the alphas density profile. It is because that the distribution of the ash is not only due to alphas slowing down but also the self-diffusion of the helium ash. On the other hand, the tendency of helium ash variation with the fueling quantity is similar to the alphas since the fueling is the basic source of both. The central density of the ash is increased about ~ 16% as the fueling quantity rising from $9.51 \times 10^{21}$ to $1.415 \times 10^{22}$.

3.2. Fusion power and burning fraction under different fueling conditions

In this section, we focus on the relationship of burning fractions and fusion power under the different fueling conditions. The tritium burning fraction can be calculated as follows,

$$f_b = \frac{\int_V n_D n_T \langle \sigma_D T \rangle J_d \psi d\psi d\xi}{\int_V S_T J_d \psi d\psi d\xi}$$  \hspace{1cm} (24)

Figure 6(a) shows the change of the fusion powers in different fuel cases. As be raised substantially by the fueling depth, the fusion power is also shown approximately proportional to the fueling quantity for a given fueling depth, e.g. the fusion power for $1.415 \times 10^{22}$s$^{-1}$ is approximately 1.5 times of that for $9.51 \times 10^{21}$. It is due to the fact that the burning fraction is hardly affected by the fueling quantity, for a given fueling depth, as shown in figure 6(b). In other words, since the burn-
Figure 5. The helium ash density profiles in steady states under the different fueling conditions, with (a) the fuel quantity of $9.51 \times 10^{21}$, (b) the fuel quantity of $1.105 \times 10^{22}$, (c) the fuel quantity is $1.26 \times 10^{22}$ and (d) the fuel quantity is $1.415 \times 10^{22}$. Also, results for various fuel positions of $\psi = 0.3$ (blue), 0.5 (yellow), 0.7 (green), and 0.9 (red) are shown.

Figure 6. (a) The fusion powers, and (b) burning fractions the under different fueling conditions.

3.3. Effects of diffusion and D-T rate

The diffusion coefficient $D_s = 0.1 \chi_s$ and D:T = 1 are assumed in above simulations. In this subsection, we fix the fuel quantity at $1.26 \times 10^{22} \text{ m}^{-1}$, and the fuel position at $\psi_0 = 0.9$, but change the diffusion and the D-T ratio.

Then $D_s = (0.1, 0.15, 0.2, 0.25, 0.3) \chi_s$ are applied to test the effect of confinement on the burning fraction. In figures 7(a) and (b), for a better particle confinement, namely $D_s = 0.1 \chi_s$, it is easily to realize the fusion power of 1GW and the burning fraction of >3%, while the fuel position is only at
\( \psi_0 = 0.9 \), very easy to be achieved. However, if the confinement gets worse, the design goal of the 1 GW fusion power plus the >3% burning fraction requires a fueling depth of 0.7, i.e. a fueling position at \( \psi_0 = 0.3 \) or deeper, hardly to be reached. In fact, the scaling of the diffusion coefficient reduces the density linearly, causing a squarely falling of fusion power and burning fraction as shown in figures 7(a) and 7(b).

For engineering design, if the cost of deepening the fueling depth is infeasible, one may try to change the D:T ratio to raise the tritium burning fraction. However, it is on the other hand with the cost of fusion power reduction. Then, one can make a balance between the two. To do the optimization, we plot the relation of burning fraction to fusion power vs. the D:T ratio in figure 8, with the fusion power in blue dots and the burning fraction as shown in figures 7(a) and 7(b).

The numerical simulation results are as follows.

(a) The fusion reaction effect is very significant in shaping the D:T ion density profiles.

(b) The fuel depth remarkably changes the shape of D/T profiles, while to alphas and helium ash, the effect is much weaker.

(c) While it is not affected by the fueling quantity much, the burning fraction is increased substantially with the fueling depth, e.g. three times as the fueling depth changes from 0.9 to 0.3.

(d) The fusion power will linearly increase with the fuel rate when the temperature fixed. Also, the fusion power monotonically increase with the fuel depth increasing.

(e) The particle confinement has a great influence on the fusion power and the burning fraction.

(f) For engineering design, if the cost of deepening the fueling depth is infeasible, one may try to change the D:T ratio to raise the tritium burning fraction. By raising the D:T ratio to the regime of above unity, one can increase the burning fraction remarkably, but with a cost of a certain level fusion power reduction.

4. Conclusion

In summary, in order to address the issue of particle control, including fusion reaction, fueling, and ash removal, in burning plasmas and to reach the goal of tritium self-sustaining, we develop a multi-species fluid model for burning plasmas including five different species (\( n_D, n_T, n_{He}, n_\alpha, n_e \)). The classical slowing down model is applied for a fluid treatment of alphas, and empirical diffusion coefficients and a pinch model are also used.

The numerical simulation results are as follows.
Acknowledgments

This work is supported by National Key Research and Development Program of China No. 2017YFE0300501 and NSFC Grant Nos. 11975087, 41674165. Useful suggestions and discussion given by Dr XuXueqiao of LLNL are also acknowledged.

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