Integrated Particle Transport Simulation of NBI Plasmas in LHD*)

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The integrated simulation code for helical plasmas, TASK3D, is improved to solve the particle transport equation and has been applied to the neutral beam injection (NBI) plasma of LHD. To solve the particle transport equation we consider two types of particle sources: ionization of neutral particles of the recycling neutral gas and ionization of neutral beams by NBI heating. The neutral particle transport code, AURORA, has been incorporated to calculate the recycling neutral particles, and the particle source by the recycling neutral gas has been evaluated. The particle source by the NBI heating neutral beam has been evaluated by FIT3D code. A particle transport simulation with three turbulent transport models has been performed. We find that the experimental results agree well with the constant turbulent transport model. The heat and particle transport simulation have also been performed to be compared with the LHD experimental plasma with different densities. The TASK3D simulation results show good agreements with experimental data.

Keywords: TASK3D, AURORA, NBI plasma, particle transport

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1. Introduction

TASK3D [1] is an integrated transport code for helical plasmas and was developed based on the TASK [2] code in a collaboration between Kyoto University and NIFS. Using the TASK3D code, we have performed the following integrated simulation of LHD plasma: (i) self-consistent calculations of the heat transport and the distribution of heating power in experimental plasmas (assuming steady state) [3], (ii) simulations of a time evolving plasma using gas puff control and power modulation [4], (iii) heat transport simulations of multi-ion-species plasmas [5], and (iv) integrated heat transport simulation of a high Ti plasma by carbon pellet injection [6]. These analyses have proven the effectiveness of integrated simulation by TASK3D.

However, in previous studies, we have assumed a fixed plasma density and have used experimentally measured density profiles to perform the heat transport simulation. Understand particle transport as well as heat transport of helical plasmas is important. Therefore, we have to simultaneously solve both the particle and heat transport. To solve the particle transport equation, the particle source of plasma and the particle transport model need to be determined.

In this study, we investigate the particle transport of LHD applying TASK3D. The plasma density is sustained by ionization of neutral particles, which are supplied by gas-puffing, neutral beam injection (NBI) heating and pellet injection. In this study, we consider two types of particle sources of the plasma: ionization of the recycling neutral gas and ionization of the neutral beams by NBI heating.

We incorporate the neutral particle transport code, AURORA [7], which can evaluate the radial profile of hydrogen neutrals in a plasma assuming neutral density and energy at the plasma boundary. Then, the particle source by the recycling neutral gas can be calculated. The particle source by NBI heating can be calculated by the FIT3D code [8], which can determine NBI heat deposition profiles including prompt orbit effect using the Monte Carlo method. We solve the particle transport equation and include these two plasma sources.

We have assumed that heat transport is the sum of neoclassical and turbulent transports described in previous studies. Thus, in this study, we also assume that particle transport is the sum of neoclassical and turbulent transports. Neoclassical transport can be evaluated by the neoclassical transport database (DGN/LHD [9]), which can calculate the neoclassical transport coefficient of particle transport. Three models for particle turbulent transport are assumed and compare with the experimental results.

Finally, we simulate heat and particle transport of pure hydrogen NBI heating plasmas. For heat transport, we assume gyro-Bohm+gradTi turbulent transport model, which was proposed in our previous studies [3, 5].

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2. Simulation Model

TASK3D is an integrated simulation code for helical plasmas and has a modular structure where modules describe physical phenomena over a broad range of time and space. To perform heat and particle transport simulation, we use six modules, i.e., VMEC [10], ER, AURORA, FIT3D, TR, and DGN/LHD in the TASK3D modules.

VMEC evaluates the MHD equilibrium in a three-dimensional magnetic configuration. FIT3D evaluates the radial profile of the NBI heating power, particle source, beam-driven current, beam ion density, and beam ion pressure. AURORA calculates the radial profile of neutral particles by Monte Carlo techniques. AURORA assumes that the plasma is cylindrical, and that the neutral particle source is mono energetic and isotropic. ER evaluates the radial electric field by the ambipolar condition of the neoclassical particle fluxes of electrons and ions.

TR calculates the radial transport of heat and particles by solving the diffusive equations given as follows,

$$\begin{aligned}&\frac{\partial}{\partial t}(n_sV') = \\ &-\frac{\partial}{\partial\rho}\left(V'\langle|\nabla\rho|\rangle n_sV_s - V'\langle|\nabla\rho|^2\rangle D_s\frac{\partial n_s}{\partial\rho}\right) + S_sV',\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{\partial}{\partial t}\left(\frac{3}{2}n_sT_s\right) = -\frac{1}{V'}\frac{\partial}{\partial\rho}\Bigg(&V'\langle|\nabla\rho|\rangle n_s\left(V_{\mathrm{K_s}} + \frac{3}{2}V_s\right) \\ &-V'\langle|\nabla\rho|^2\rangle\left(\frac{3}{2}D_sT_s\frac{\partial n_s}{\partial\rho} + n_s\chi_s\frac{\partial T_s}{\partial\rho}\right)\Bigg) + P_s,\end{aligned} \tag{2}$$

where D_s is the particle transport coefficient, χ_s is the thermal conductivity, V_s is the particle pinch velocity, and $V_{\mathrm{K_s}}$ is the heat pinch velocity. In this study in order to compare with experimental results we set the boundary conditions for the temperature and density to the experimental values.

Neoclassical components of D_s, V_s, $V_{\mathrm{K_s}}$, and χ_s are determined by DGN/LHD, which is a neoclassical transport data base, and we assume that the turbulence components of D_s, V_s, and $V_{\mathrm{K_s}}$ are zero. We also assume a quasi-neutral plasma and determine the electron density by $n_{\mathrm{e}} = \sum^{\mathrm{ion}} Z_sn_s$. We assume that heat and particle diffusion coefficients are given by the sum of the turbulence transport term and the neoclassical transport term.

$$\chi_s = \chi_s^{\mathrm{NC}} + \chi_s^{\mathrm{TB}},\ D_s = D_s^{\mathrm{NC}} + D_s^{\mathrm{TB}}, \tag{3}$$

where $\chi_s^{\mathrm{NC}}, \chi_s^{\mathrm{TB}}, D_s^{\mathrm{NC}}$ and D_s^{TB} are the neoclassical thermal conductivity, the turbulence thermal conductivity, the neoclassical particle transport coefficient and the turbulence particle transport coefficient, respectively.

For the turbulence component of heat transport we apply the gyro-Bohm model for electrons and gyro-Bohm+gradTi model for ions [3].

$$\chi_{\mathrm{e}}^{\mathrm{TB}} = C_{\mathrm{e}}\left(\frac{T_{\mathrm{e}}}{eB}\right)\left(\frac{\rho_{\mathrm{e}}}{L}\right), \tag{4}$$

$$\chi_{\mathrm{i}}^{\mathrm{TB}} = C_{\mathrm{i}}\left(\frac{T_{\mathrm{i}}}{eB}\right)\left(\frac{\rho_{\mathrm{i}}}{L}\right)\left(\frac{aT'_{\mathrm{ave}}}{T_{\mathrm{ave}}}\right), \tag{5}$$

where $T_{\mathrm{ave}} = (T_{\mathrm{e}} + T_{\mathrm{i}})/2$, ρ_{e}, ρ_{i}, B, and L are the average temperatures of the electrons and ions, the Larmor radius of the electron, the Larmor radius of the ion, the magnetic field strength, and the minor radius, respectively. We use constant factors $C_{\mathrm{e}} = 1.51$, $C_{\mathrm{i}} = 0.57$ as in our previous study [3].

For the turbulence component of the particle transport, we apply three turbulent transport models: the constant model, the gyro-Bohm model, and the Alcator model.

$$D_s^{\mathrm{TB}} = C_0 \cdots \text{ constant model}, \tag{6}$$

$$D_s^{\mathrm{TB}} = C_1\left(\frac{T_s}{eB}\right)\left(\frac{\rho_{\mathrm{e}}}{L}\right)\cdots \text{gyro} - \text{Bohm model}, \tag{7}$$

$$D_s^{\mathrm{TB}} = C_2\frac{1}{n_s}\cdots \text{Alcator model}, \tag{8}$$

where C_0, C_1, C_2 are constant factors. We find appropriate values of these constants using the reference experimental plasma and apply the other plasmas to fix the values of the constants. In this study, we also determine the appropriate turbulent transport model by comparing with experimental results.

3. Simulation Results

We investigate heat and particle transport in an NBI plasma of LHD applying the TASK3D code. We assume the magnetic configuration of LHD as $R_{\mathrm{ax}} = 3.6$ [m] and set the central magnetic field strength as $B_0 = 2.75$ [T]. More than 25 MW of NBI heating power is injected into the hydrogen plasma.

3.1 Particle transport simulation

First, we study particle transport assuming the experimentally measured ion and electron temperatures and select the appropriate turbulent transport model and constant parameter to fit the experimental results. To solve the particle transport equation, the radial profile of the particle source is needed. In this study, we assume two kinds of particle sources: the ionization of the neutral particles and the NBI injected neutral beams.

We calculate the radial profile of the neutral particles originating from gas-puff and/or the wall using the AURORA code and the particle source is calculated by multiplying by the ionization rate of neutral particles. The particle source generated by the NBI beams are calculated using FIT3D. We solve the particle transport equation in the NBI plasmas applying three turbulent transport models with fixed temperature profiles.

To study how the turbulent transport model can be used to fit experimental results, we selected a typical quasi steady state discharge of hydrogen NBI heating plasma as the reference plasma, whose density and temperature profiles are shown in Fig. 1 (a). We apply TASK3D to this reference plasma to find an appropriate turbulent transport model and a constant parameter.

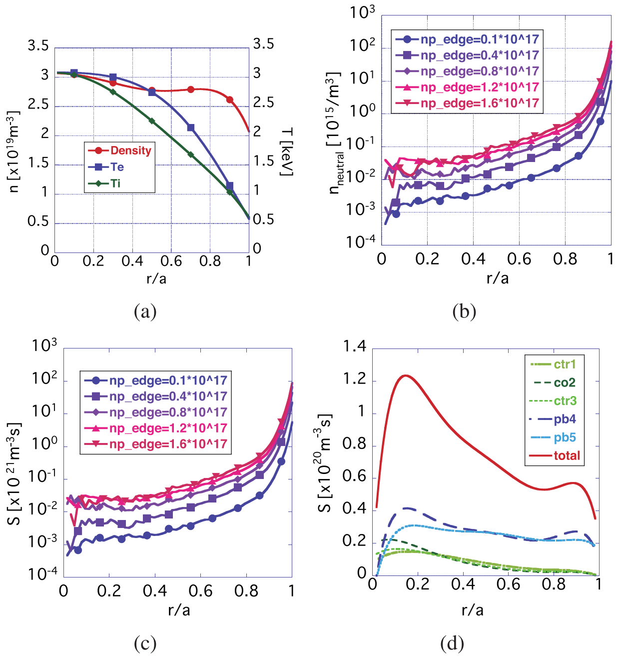


Fig. 1 (a) Radial profile of the plasma parameters, (b) the density of neutrals from the wall, (c) the particle source from the neutral particles and (d) the particle source from the NBI beams of the LHD experimental result #109081.

The radial profile of the hydrogen neutral particles is evaluated by the AURORA code. The neutral particle temperature at the edge is assumed to be 10 eV. In Figs. 1 (b) and (c), the radial profiles of the neutral particle densities and the particle sources are shown for a range of edge neutral densities. In this model, neutral particle densities and particle sources both decay exponentially from the edge region.

Five neutral beam injectors are installed in the NBI heating systems of LHD; three tangential injectors (#ctr1, #co2 and #ctr3) and two perpendicular injectors (#4pb and #5pb). These NBI heating systems efficiently heat the plasma and also act as a source of the particles. In Fig. 1 (d), the radial profile of the particle source by NBI heating ($P_{\#1}$ = 6.06 [MW], $P_{\#2}$ = 4.41 [MW], $P_{\#3}$ = 4.71 [MW], $P_{\#4}$ = 5.32 [MW], $P_{\#4}$ = 5.71 [MW]) is shown. The Particle source of the tangential injection beam has a peak around $r/a = 0.1$ and exponentially decays from the core to the edge. The particle sources created by the perpendicular injection beams also have maximum densities around $r/a = 0.1$ but slowly decay from core to edge. We find that the particle source from NBI beams dominates in the core region and the particle source from the neutral particles dominates in the edge region.

We perform the particle transport simulations of NBI plasmas with different turbulent transport models. We fix the edge neutral density, $n_{\mathrm{neutral}}^{r/a=1}$, as $n_{\mathrm{neutral}}^{r/a=1} = 0.4 \times 10^{17}$ [1/m^3], because we found that the obtained results shows relatively good agreements around this $n_{\mathrm{neutral}}^{r/a=1}$ value in all model cases. Therefore, we investigate appropriate constant factors by comparing with experimental results.

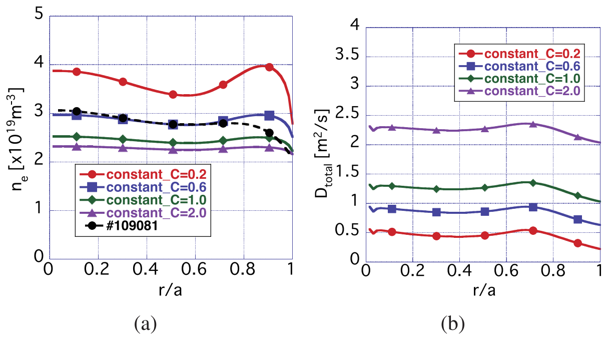


Fig. 2 Radial profile of (a) the ion densities and (b) the particle transport coefficients (b) with constant turbulent transport model (the constant factor is assumed to be C = 0.2, 0.6, 1.0, and 2.0).

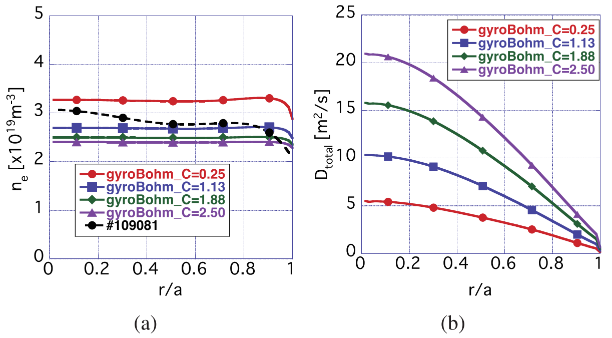


Fig. 3 Radial profile of (a) the ion densities and (b) the particle transport coefficients with gyro-Bohm turbulent transport model (the constant factor is assumed to be C = 0.25, 1.13, 1.88, and 2.50).

First, we apply the constant turbulent transport model and vary the constant parameter. In Fig. 2, the results of the plasma density and the particle diffusion coefficients obtained are shown. The most appropriate constant factor within the assumed condition was found to be $C = 0.6$. The radial density profile of the simulation result ($C = 0.6$) has a small peak in the core region and agrees well with the experimental data (#109081). The radial profile of the particle transport coefficient is almost flat, and the turbulent transport coefficient becomes dominant in edge region.

Next, we incorporated the gyro-Bohm model and varied the the constant parameter. In Fig. 3, the results of the plasma density and the particle transport coefficients obtained are shown. The most appropriate constant factor within this assumed condition is $C = 1.13$. The radial density profile of the simulation result ($C = 1.13$) is flat in core region. The radial profile of the particle transport coefficient monotonically increases from the edge to the core due to the temperature dependency of gyro-Bohm model.

Finally, we incorporate the Alcator model and varied the constant parameter. In Fig. 4, the results of the plasma

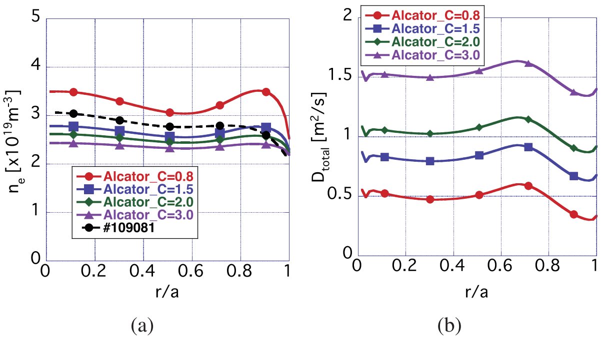


Fig. 4 Radial profile of (a) the ion densities and (b) the particle transport coefficients with Alcator turbulent transport model (the constant factor is assumed to be C = 0.8, 1.5, 2.0, and 3.0).

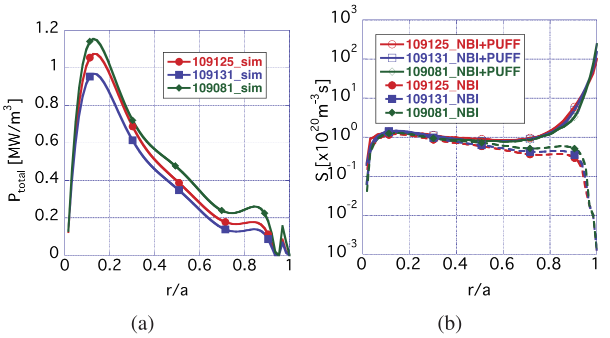


Fig. 5 Radial profile of (a) the heat source depositions and (b) the particle source depositions.

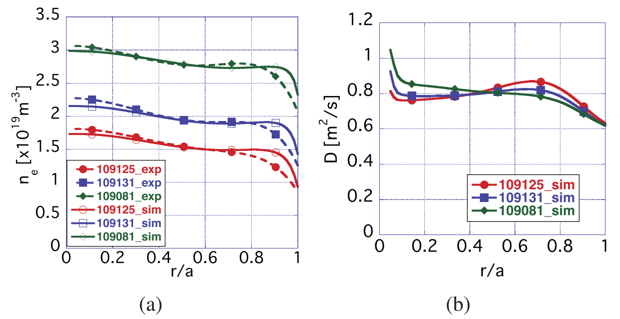


Fig. 6 Radial profile of (a) the densities and (b) the particle transport coefficients.

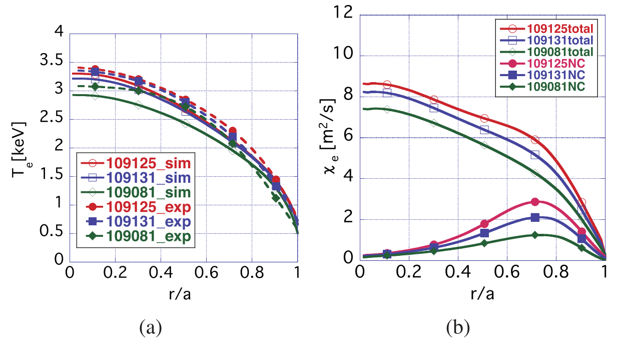


Fig. 7 Radial profile of (a) the electron temperatures and (b) the heat transport coefficients (total and neoclassical) of electron.

density and the particle transport coefficients obtained are shown. The most appropriate constant factor within this assumed condition is found to be $C = 1.5$. The radial density profile of the simulation result ($C = 1.5$) has a small peak in the core region and agrees with the experimental data. The radial profile of the particle transport coefficient is flat due to the density dependency of the Alcator model.

Overall, we conclude that the constant turbulent transport model with $C = 0.6$ is appropriate for the particle transport to reproduce the experimental results of the NBI heating plasma (#109081).

3.2 Heat and particle transport simulation

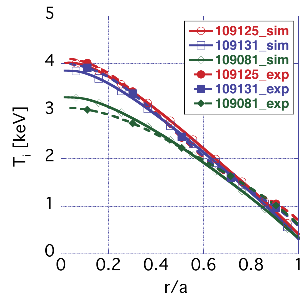
Next, we performed the heat and particle transport simulation of NBI plasmas and compared the experimental results with three different densities (#109081, #109131, and #109125). We assume the magnetic configuration of LHD as $R_{\mathrm{ax}} = 3.6$ [m], total input of NBI as $P_{\mathrm{total}} = 26.2$ [MW] and set the central magnetic field strength as $B_0 = 2.75$ [T].

In Fig. 5, the NBI heat depositions and particle sources are shown. The heat depositions and particle sources by NBI heating decrease with decreasing plasma density because of the increase of the shine through loss of beam ions. On the other hand, the particle source profile created by neutral particles from the edge increases as the plasma density decreases because a thinner plasma density enhances the neutral particle radial transport. The radial profiles of plasma density are almost flat and have small peaks in three density cases, agreeing well with the experimental data (Fig. 6 (a)). In Fig. 6 (b) the radial profiles of particle transport coefficients in the three density cases are shown, and we can see that the coefficients have a slight dependence on the density values due to differences in the neoclassical transport values.

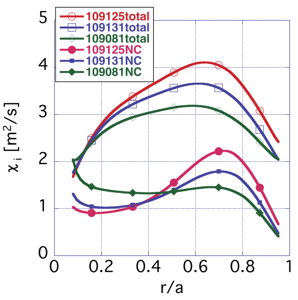
In Fig. 7, the electron temperatures and heat transport coefficients in the three density cases are shown. The electron temperature does not strongly depend on the plasma density, and the turbulent transport is dominant when compared with the neoclassical one. The simulated and the experimental results agree well. The ion temperatures indicate a weak dependence on the density and the turbulent transport coefficient is two to four times larger than the neoclassical one (Fig. 8). The ion temperatures obtained relatively good agreements with experimental results.

4. Conclusion

We have improved the integrated simulation code (TASK3D) for helical plasmas to solve the particle transport equation and have applied it to the NBI plasma of LHD. We have considered two kinds of particle sources:



(a)



(b)

Fig. 8 Radial profile of (a) the ion temperatures and (b) the heat transport coefficients (total and neoclassical) of electron.

ionization of neutral particles of the recycling neutral gas and ionization of the neutral beams by NBI heating. The neutral particle transport code (AURORA) has been incorporated to calculate the recycling neutral particles and the particle source generated by the recycling neutral gas has been calculated. The particle source by the NBI heating of the neutral beam has been evaluated by the FIT3D code.

We have studied a particle transport simulation of the reference NBI heating plasma assuming three turbulent transport models. We find that the constant turbulent transport model agrees well with the experimental results of the reference plasma. Next, we have performed a heat and particle transport simulation to compare with the LHD experimental plasma for three different densities. The TASK3D simulation results have shown relatively good agreement with experimental data assuming a constant turbulent model with the same constant parameter.

These results suggest the particle transport properties of the NBI heat plasma of LHD would play an important role in designing a future fusion reactor based on the heliotron configuration.

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